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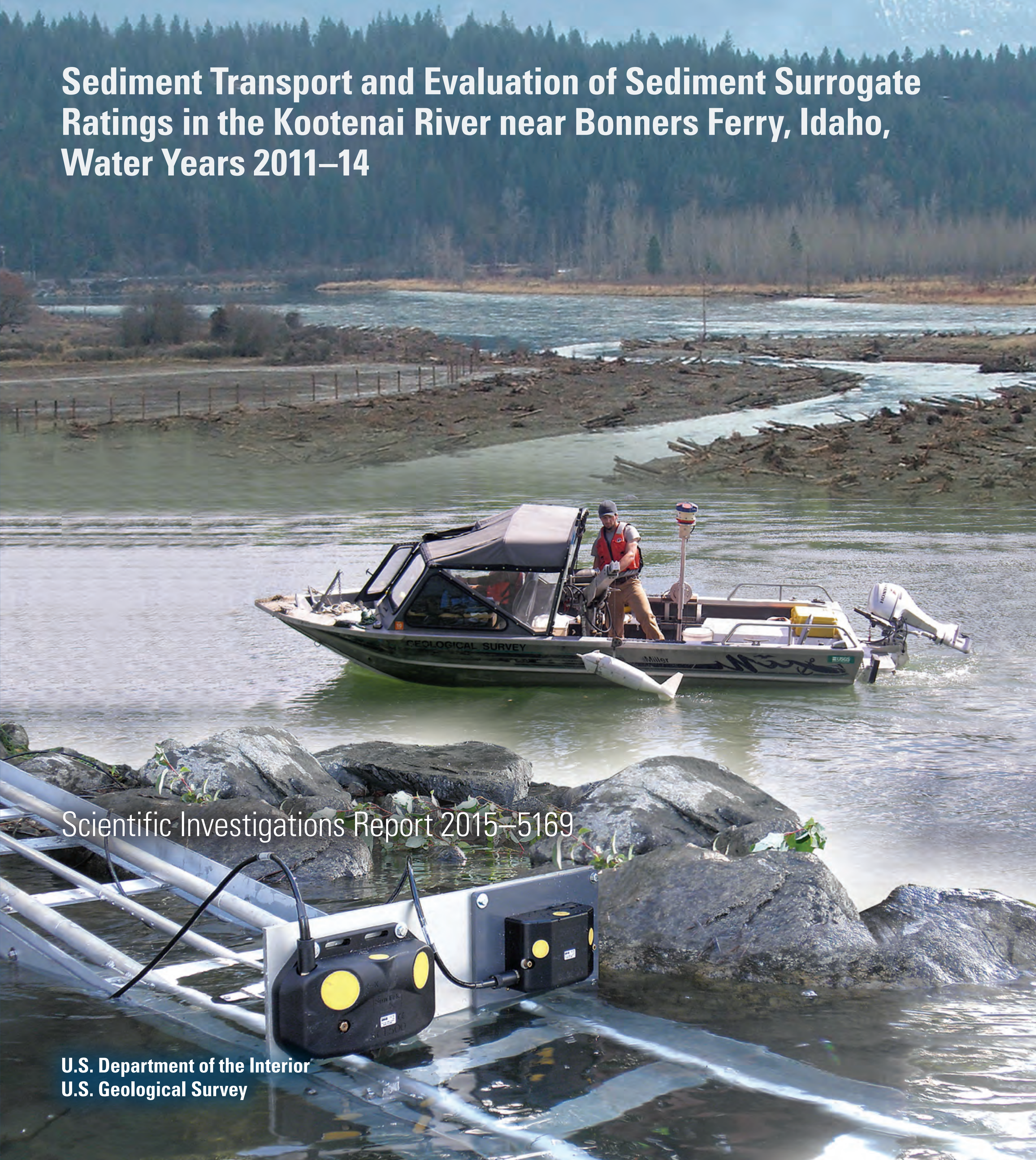
Sediment Transport and Evaluation of Sediment Surrogate Ratings in the Kootenai River near Bonners Ferry, Idaho, Water Years 2011–14



Scientific Investigations Report 2015–5169

U.S. Department of the Interior
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Cover: Montage of three photographs:
(Foreground) 1.5 and 3.0 megahertz acoustic Doppler velocity meters attached to an aluminum slide track mount), near Bonners Ferry, Kootenai River, Idaho. (Photograph by Molly Wood, U.S. Geological Survey, August 30, 2010.)

(Middle) U.S. Geological Survey employees collecting a suspended sediment sample, near Bonners Ferry, Kootenai River, Idaho. (Photograph by Ryan Fosness, U.S. Geological Survey, June 9, 2010).

(Background) Constructed channel features and changes in the Phase 1A side channel restoration area, near Bonners Ferry, Kootenai River, Idaho. (Photograph by Molly Wood, U.S. Geological Survey, November 30, 2011).

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U.S. Department of the Interior
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Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Mass	
ton, short (2,000 lb)	0.9072	megagram (Mg)
ton per day (ton/d)	0.9072	metric ton per day
ton per day (ton/d)	0.9072	megagram per day (Mg/d)
ton per year (ton/yr)	0.9072	megagram per year (Mg/yr)
ton per year (ton/yr)	0.9072	metric ton per year

International System of Units to Inch/Pound

Multiply	By	To obtain
	Volume	
liter (L)	33.82	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Supplemental Information

Concentrations of chemical constituents in water are given in either milligrams per liter (mg/L) or micrograms per liter (µg/L).

Sediment Transport and Evaluation of Sediment Surrogate Ratings in the Kootenai River near Bonners Ferry, Idaho, Water Years 2011–14

By Molly S. Wood, Ryan L. Fosness, and Alexandra B. Etheridge

Abstract

The Kootenai River white sturgeon (*Acipenser transmontanus*) and other native fish species are culturally important to the Kootenai Tribe of Idaho, but their habitat and recruitment have been affected by anthropogenic changes to the river. Although the interconnections among anthropogenic changes and their impacts on fish are complex, the Kootenai Tribe of Idaho, in cooperation with other agencies, has been trying to understand and promote native fish recruitment through the development and implementation of the Kootenai River Habitat Restoration Program. As part of this effort, the U.S. Geological Survey collected sediment and streamflow information and evaluated use of acoustic backscatter as a sediment surrogate for estimating continuous suspended-sediment concentration at three sites in the Kootenai River white sturgeon critical habitat during water years 2011–14.

During the study, total suspended-sediment and fines concentrations were driven primarily by contributions from tributaries flowing into the Kootenai River between Libby Dam and the study area and were highest during rain-on-snow events in those tributary watersheds. On average, the relative percentage of suspended-sediment concentration in equal-width-increment samples collected in water years 2011–14 composed of fines less than 0.0625 mm (called washload) was 73, 71, and 70 percent at the Below Moyie, Crossport, and Tribal Hatchery sites, respectively. Suspended sand transport often increased with high streamflows, typically but not always associated with releases from Libby Dam. Bedload measured at the Crossport site was about 5 percent, on average, of the total sediment load measured in samples collected in water years 2011–13 and was positively correlated with suspended-sediment load. Comparisons with regional regression and envelope lines for suspended-sediment and bedload transport in relation to unregulated drainage area (drainage area downstream of Libby Dam) show that sediment transport was substantially less in the Kootenai River than in selected, minimally regulated Rocky Mountain rivers.

Acoustic surrogate ratings were developed between backscatter data collected using acoustic Doppler velocity meters (ADVMs) and results of suspended-sediment samples. Ratings were successfully fit to various sediment size classes (total, fines, and sands) using ADVMs of different frequencies (1.5 and 3 megahertz). Surrogate ratings also were developed using variations of streamflow and seasonal explanatory variables. The streamflow surrogate ratings produced average annual sediment load estimates that were 8–32 percent higher, depending on site and sediment type, than estimates produced using the acoustic surrogate ratings. The streamflow surrogate ratings tended to overestimate suspended-sediment concentrations and loads during periods of elevated releases from Libby Dam as well as on the falling limb of the streamflow hydrograph. Estimates from the acoustic surrogate ratings more closely matched suspended-sediment sample results than did estimates from the streamflow surrogate ratings during these periods as well as for rating validation samples collected in water year 2014. Acoustic surrogate technologies are an effective means to obtain continuous, accurate estimates of suspended-sediment concentrations and loads for general monitoring and sediment-transport modeling. In the Kootenai River, continued operation of the acoustic surrogate sites and use of the acoustic surrogate ratings to calculate continuous suspended-sediment concentrations and loads will allow for tracking changes in sediment transport over time.

Introduction

The Lower Ktunaxa (modern day spellings include Kutenai, Kootenai, and Kootenay) people, hereinafter Kootenai people, have a long and proud history as skilled canoeing and fishing people. Using bark canoes to navigate the lower Kootenai River (called Kootenay River in Canada) and Kootenay Lake, the Lower Kootenai people used a wide variety of methods to harvest fish. Fishing techniques included hook and line, a variety of spears, basket traps as large as 10 × 3 ft, and wicker weirs to harvest fish from lakes, sloughs, rivers and fishing through ice (Hodge, 1913). The Kootenai people depended on the local fish species, such as resident fish populations of white sturgeon (*Acipenser transmontanus*), burbot (*Lota lota*), and native trout species, as a major source of food (Hodge, 1913; Kootenai Tribe of Idaho, 2009). Today, the Kootenai River white sturgeon and burbot remain culturally important; however, both fish species are no longer harvested because of critically low wild populations (Kootenai Tribe of Idaho, 2009).

Kootenai River white sturgeon are a genetically distinct population restricted to Kootenay Lake in British Columbia, Canada, and inhabit about 116 river miles of the Kootenai River in British Columbia, Idaho, and Montana (fig. 1). Bonnington Falls (current location of Corra Linn Dam), located at the outlet of Kootenay Lake in British Columbia, and Kootenai Falls in Montana are natural barriers that have isolated fish species in the lower Kootenai River after the last glacial advance (Northwest Power and Conservation Council, 2005). Decreasing population numbers and a lack of natural recruitment of white sturgeon were first noted in the mid-1960s (Partridge, 1983; Federal Register, 1994; U.S. Fish and Wildlife Service, 1999). In 1994, the U.S. Fish and Wildlife Service (USFWS) listed the Kootenai River population of white sturgeon as an endangered species under the provisions of the Endangered Species Act (ESA) of 1973, as amended. A critical habitat reach was designated in the Kootenai River extending 7 mi upstream and 11.3 mi downstream of Bonners Ferry (Federal Register, 2008; fig. 1).

Additionally, a substantial burbot fishery (sport and commercial) also was present on the Kootenai River until the mid- to late-1970s. Sampling efforts in 1979 showed a 96-percent decrease in the Kootenai River burbot population compared to similar sampling efforts in 1958 (Paragamian and others, 2000). Because of the collapse of the burbot population, the fishery was closed to harvest in the U.S. waters in 1992, and later closed in Canada in 1997 (Paragamian and others, 2000).

The collapse of the Kootenai River white sturgeon, burbot, and other native aquatic species are thought to be the result of a combination of anthropogenic changes, which began at the turn of the 19th century, in the Kootenai River drainage basin,. The anthropogenic changes, including mining, timber harvest, dike and levee construction, construction of dams, nutrient effluent discharge, and increased agricultural activities, have considerably altered the Kootenai River streamflow and sediment transport regimes and have negatively affected white sturgeon and other fish species (Anders and others, 2007; Kootenai Tribe of Idaho, 2009). Corra Linn Dam, put into service in 1931, has increased the stage of Kootenay Lake and increased the extent and duration of backwater in the lower Kootenai River (Barton, 2004). Dikes were built on natural levees early in the 20th century to protect agricultural areas in the Kootenai River floodplain from flooding (Turney-High, 1969; Boundary County Historical Society, 1987; Redwing Naturalists, 1996). The construction of dikes prevented sediment deposition in the overbank areas, constraining sediment to the main channel (Barton, 2004). Additionally, the construction and operation of Libby Dam, put into service in 1972, reduced the magnitude of streamflow and total sediment transported in the river. A combination of increased backwater, reduced streamflow magnitude, and confinement of sediment to the main river channel has created unsuitable habitat to sustain natural recruitment of the Kootenai River white sturgeon and other native fish species (U.S. Fish and Wildlife Service, 1999; Kootenai Tribe of Idaho, 2009).

White sturgeon and burbot spawning has not successfully occurred in the Kootenai River since the completion of Libby Dam. Historical white sturgeon spawning site selection and habitat prior to anthropogenic changes in the Kootenai River drainage basin is largely unknown. In recent years, most white sturgeon have attempted to spawn in reaches downstream of Bonners Ferry with a sand dominated surficial substrate (Paragamian and others, 2001). The sand substrate is an unsuitable spawning habitat as the eggs adhere to the sand and suffocate as more sand is deposited, which limits natural recruitment (Kock and others, 2006). Gravel and cobbles provide a more suitable substrate for spawning and are located upstream of Bonners Ferry, although white sturgeon rarely occupy or spawn in this reach. The interactions among channel substrate, sediment transport, streamflow, and river channel features and their effect on successful spawning and recruitment of native fish species are complex, requiring long-term data collection, analysis, and modeling.

Kootenai River Habitat Restoration Program

The U.S. Geological Survey (USGS), in cooperation with the Kootenai Tribe of Idaho (KTOI), is part of an interagency habitat restoration effort to restore natural recruitment of Kootenai River white sturgeon and other fish species. The Kootenai River Habitat Restoration Program, led by KTOI, is a collaborative, adaptively implemented and managed, and ecosystem-based restoration program. Program objectives include restoring and maintaining habitat conditions in a 55-mi reach of the Kootenai River in Idaho that support all life stages of endangered Kootenai River white sturgeon and other native fish species, including bull trout (*Salvelinus confluentus*), westslope cutthroat trout (*Oncorhynchus clarki lewisi*), Columbia River redband trout (*Oncorhynchus mykiss gairdnerii*), kokanee (*Oncorhynchus nerka*), and burbot. From 2002 through 2009, efforts primarily focused on data collection and analysis to characterize the existing habitat conditions. One- and two-dimensional hydrodynamic models were developed by various agencies and consultants, including the USGS Geomorphology and Sediment Transport Laboratory and River Design Group, Inc. (RDG), to simulate various streamflow and sediment transport scenarios using empirical data. During this same period, the focus of the habitat restoration effort shifted from a single species (white sturgeon) to an ecosystem-based approach inclusive of all aquatic species (Kootenai Tribe of Idaho, 2009).

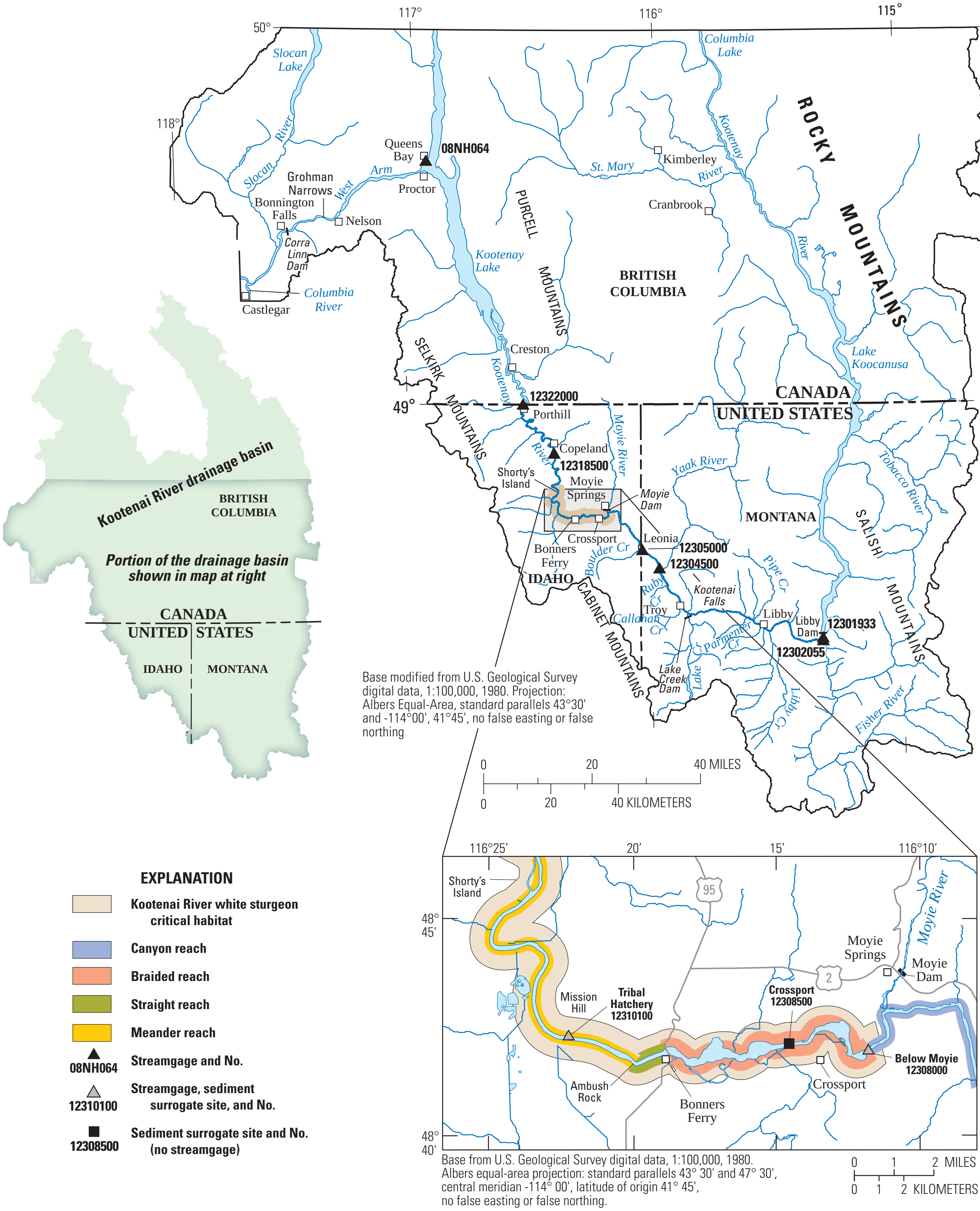


Figure 1. Kootenai River drainage basin in U.S. and Canada, and locations of streamgage and sediment monitoring sites in the Kootenai River, Idaho, water years 2011–14.

In July 2009, the KTOI developed and presented a "Master Plan" implementing adaptive management restoration projects in the critical habitat of the Kootenai River. The KTOI maintains that an ecosystem-based, watershed scale, adaptive management recovery approach will provide the best chance for the recovery of Kootenai River native fish species (Northwest Power and Conservation Council, 2005; Kootenai Tribe of Idaho, 2009). The first habitat restoration construction implementation began in 2011, and many other projects are planned for completion by 2017 and beyond (Kootenai Tribe of Idaho, 2013). The first three restoration projects were designed and constructed in what is called the "braided reach" of the Kootenai River upstream of Bonners Ferry (fig. 1). Restoration objectives include the construction of a river channel that remains sustainable and functional under the current streamflow and sediment conditions. Restoration projects were designed to protect stream banks in the riparian corridor and allow for sediment deposition on a newly constructed floodplain. Over time, the protected stream banks and constructed floodplain areas are expected to continue to develop, benefiting from annual sediment deposition. Additional restoration designs include the construction of deep pools intermittently spaced throughout the braided reach. The pools were designed to provide water depth and velocities preferred by white sturgeon.

In water year[1] 2011, the USGS began a study to measure sediment concentrations and loads and to continuously monitor sediment transport using surrogate technologies at three sites in the critical habitat to further characterize the river's response to altered streamflow and sediment transport regimes. Sediment and streamflow data collected as part of this study have been used to calibrate and verify one- and two-dimensional models used in the design of various restoration projects. In the future, continuously monitored sediment data from this study may provide a method to evaluate any influence of the restoration projects on sediment transport (Kootenai Tribe of Idaho, 2009; 2011).

Purpose and Scope

This report documents findings on the basis of sediment and streamflow data collected by the USGS in the Kootenai River near Bonners Ferry, Idaho, in 2011–14. The purpose of this report and associated data is to document suspended and bed sediment transport conditions for use in KTOI, USGS Geomorphology and Sediment Transport Laboratory, and RDG efforts to evaluate habitat, to model sediment transport, and to design and adaptively manage river channel modifications to encourage recruitment and survival of white sturgeon and other native fish species in the Kootenai River. This report also describes comparisons between sediment transport estimation techniques using streamflow and emerging techniques using acoustic surrogate technology.

[1]A water year is defined as the 12-month period from October 1 for any given year through September 30 of the following year. The water year is designated by the calendar year in which the water year ends. All reference to years and periods is to water years.

Description of Study Area

River Features and Climate

The Kootenay River headwaters originate in the Rocky, Salish, and Purcell Mountains of British Columbia, Canada (fig. 1). From the headwaters, the Kootenai River flows south through northwestern Montana, and then turns west to the base of the Cabinet Mountains, where it flows north through the Kootenai Valley of northern Idaho and enters Kootenay Lake, a natural lake at the base of the Selkirk Mountains in British Columbia. From Kootenay Lake, the river flows about 16.1 river miles until reaching its mouth at the Columbia River near Castlegar, British Columbia. The Kootenai River is about 485 mi long (measured from the confluence with the Columbia River to the approximate headwaters) and drains an area of about 19,300 mi^2. Drainage basin elevations range from about 11,900 ft at the river's headwaters to about 1,745 ft at Kootenay Lake and about 1,468 ft at the confluence with the Columbia River (Columbia Basin Inter-Agency Committee, 1965; Berenbrock, 2005).

The Kootenai River drainage basin climate is highly variable depending on elevation and rain shadow effect. Mean annual precipitation averages about 30 in. for the Kootenai River drainage basin in Idaho and ranges from 14 in. in the dry parts of British Columbia, to an average of 60 in. on some of the high elevation mountains (TetraTech, Inc., 2004). August and September are generally the driest periods of the year (less than 1.2 in. of precipitation per month). At the lowest elevations the average daily maximum temperature is about 84 °F in July and August. Winters' average temperatures range from about 26 to 38 °F from November through March. Cooler, subzero temperatures are common, especially in high elevations. Mean annual snowfall ranges from about 40 in. in low elevation valleys to more than 300 in. in high elevation mountain areas with the most snowfall occurring November through March (TetraTech, Inc., 2004). The highest streamflow runoff period generally occurs in mid- to late-spring and is largely caused by the spring snowmelt runoff (TetraTech Inc., 2004; Kootenai Tribe of Idaho, 2009).

Two dams are located on the main stem Kootenai River and Kootenay Lake—Corra Linn Dam near Nelson, British Columbia, and Libby Dam near Libby, Montana (fig. 1). Large tributaries between Libby Dam and study sites include the Fisher River, Libby Creek, Pipe Creek, Lake Creek, Callahan Creek, Yaak River, Boulder Creek, and Moyie River (Columbia Basin Inter-Agency Committee, 1965). The USGS currently (as of 2015) operates real-time streamgages on the Fisher River (USGS 12302055) and Yaak River (USGS 12304500) (fig. 1), which give an indication of tributary inflows between Libby Dam and the study sites.

The Kootenai River consists of four geomorphic channel patterns, hereinafter called reaches, between Libby Dam and Kootenay Lake—canyon, braided, straight, and meander reaches (fig. 1). The canyon reach extends 58.8 mi from Libby Dam to about 1.2 mi downstream of the confluence of the Moyie River (also the upstream extent of critical habitat). The Kootenai River in the canyon reach is predominantly a single threaded channel confined to a narrow, deep canyon consisting of riffle, run, pool, and glide sequences. Median particle size of the riverbed ranges from coarse cobble to coarse gravel and generally decreases in size from the upper to lower extent (Berenbrock, 2005; Burke and others, 2006; Fosness and Williams, 2009). The braided reach begins at the end of the canyon reach where the canyon transitions to a wider valley with a defined floodplain. The Kootenai River traverses about 7 mi around numerous islands, side channels, and meanders in the braided reach. Median particle size of the riverbed ranges from fine gravel to coarse gravel (Fosness and Williams, 2009). A number of pools, riffles, run, and glide sequences are located in the main channel in the upper one-half of the braided reach. The channel in the lower one-half of the braided reach within the Kootenay Lake backwater transition zone is predominantly wide, shallow, and lacking a well-defined thalweg. Levees are present at various locations on both sides of the river in the braided reach. The straight reach is between the U.S. Highway 95 Bridge and a prominent bedrock outcropping locally known as Ambush Rock, near Bonners Ferry, Idaho (fig. 1). The straight reach has high, rip-rap covered banks, natural and manmade levees, and includes roads, bridges, and levees built in the early 20th century. Influenced much of the year by backwater from Kootenay Lake, the straight reach is the beginning of a depositional zone for sand (Berenbrock, 2005). Riverbed sediment in the upstream one-half of the straight reach is predominantly gravel, and transitions into predominantly sand at Ambush Rock. Extending from Ambush Rock to the confluence with Kootenay Lake, the meander reach winds about 78 mi. Average width in the meander reach is about 600 ft with depths exceeding 100 ft in scoured meander bends. Levees line the entire top of the bank on both sides of the river throughout the meander reach. The abandoned floodplain spans 2–3 mi wide. Sand is the dominant substrate in the riverbed in the meander reach and is mixed with intermittent compacted lacustrine clay features and sparsely distributed patches of gravel (Snyder and Minshall, 1996; TetraTech, Inc., 2004).

Streamflow Regulation

The Kootenai River downstream of Libby Dam has largely been a regulated system after Libby Dam was completed in 1972, effectively regulating nearly one-half (8,985 mi^2) of the 19,300 mi^2 Kootenai subbasin (Tetra Tech, Inc., 2004). Current flood control operations at Libby Dam, referred to as variable discharge or streamflow (VARQ), began in 2003 and were designed not only to maintain flood control operations but also to increase outflows during the spring to simulate natural spring runoff, called “freshet” streamflows and to meet streamflow needs for ESA species (U.S. Army Corps of Engineers, 2008). The magnitude and duration of the streamflow have been altered by VARQ operations, most notably in the spring and autumn. Unregulated tributaries between Libby Dam and the study area contribute streamflow, however, most notably during the spring freshet. As part of VARQ, the U.S. Army Corps of Engineers (USACE) manage releases from Libby Dam in May or June to simulate streamflow conditions that existed prior to the construction of the dam, which are considered favorable to sturgeon spawning, commonly referred to as the “sturgeon pulse” (U.S. Army Corps of Engineers, 2005). Additionally, increased outflows from Libby Dam occur during winter operations, referred to as winter power ramping and Flood-Risk Management (FRM) outflows. Increased regulated outflows from Libby Dam in the spring and winter typically result in a bimodal pattern in mean monthly streamflow that was not present prior to regulation.

Sediment Sources

Lake Kookanusa, the reservoir created by Libby Dam, traps about 90 percent of suspended sediment and 100 percent of coarse-grained sediment (Kootenai Tribe of Idaho, 2009). Moyie Dam, on the Moyie River 2.3 mi upstream of the confluence with the Kootenai River, traps sediment from the Moyie River drainage basin (fig. 1). After the construction of Libby Dam, sources of sediment transported through the critical habitat have been limited to tributaries downstream of Libby Dam and erosion from the bed and stream bank in the main channel of the Kootenai River. The quantity of sediment transported can vary depending on a combination of the magnitude, duration, and origin of the streamflow. Fisher River and Boulder Creek both have elevated sediment transport rates because of a combination of geographical and geological settings and forest practices (TetraTech, Inc., 2004). A road removal restoration project completed in 2008 on the lower Fisher River watershed was intended to reduce bank erosion and restore the floodplain. The Fisher River restoration project probably reduced the sediment transport load, although sediment samples would need to be collected to quantify any changes (Sugden, 2012). Stream banks in the Kootenai River braided reach commonly have a gravel sublayer and a top layer consisting of remnant fine sands and silt. Bank erosion was noted to account for about 15–30 percent of the bed material in the braided reach (Kootenai Tribe of Idaho, 2009). Prior to the start of restoration efforts, bank erosion in the middle to lower parts of the braided reach was the largest local source of sediment contribution in the critical habitat reach, estimated to be about 66,200 tons in 2008 (Kootenai Tribe of Idaho, 2009). The spring freshet typically is the period of highest streamflow, sediment concentrations, and backwater extent into the braided reach. The combination of high sediment concentration and backwater result in the deposition of sands in the braided reach. During the elevated FRM streamflows in the winter, streamflow is predominantly sediment-free water from Libby Dam. Additionally, the backwater extent is typically at its lowest coincident with lower Kootenay Lake levels. The combination of high streamflow, relatively low sediment concentrations, and minor backwater conditions allows for the sediment deposited previously in the spring to become mobilized and transported into the meander reach (Fosness and Williams, 2009).

Study Sites

Three sites were selected for this study for sediment data collection during 2011–14 (fig. 1):

- USGS 12308000, Kootenai River below Moyie River, near Bonners Ferry, Idaho (hereinafter called the Below Moyie site), located at river mile (RM) 159.6 at the upstream end of the braided reach and white sturgeon critical habitat, at the transition between the canyon and braided reaches;
- USGS 12308500, Kootenai River at Crossport, near Bonners Ferry, Idaho (hereinafter called the Crossport site), located at RM 156.8 in the braided reach; and
- USGS 12310100, Kootenai River at Tribal Hatchery, near Bonners Ferry, Idaho (hereinafter called the Tribal Hatchery site), located at RM 149.9 in the meander reach.

Study sites were selected primarily to measure suspended-sediment transport in the upstream end of the braided reach, the middle of the braided reach, and upstream end of the meander reach, and to coincide with key locations for the restoration design and sediment modeling efforts. Suspended-sediment samples were collected at all three sites, and bedload samples were collected at the Crossport site. The study sites were co-located with USGS streamgages at the Below Moyie and Tribal Hatchery sites. A streamgage was not present at the Crossport site, but streamflow was considered to be the same as at the Below Moyie site because of the short distance between sites, no surface water inflows or outflows, and results of verification measurements.

Previous Investigations

Sediment Data Collection and Analysis

The collection of sediment transport data by the USGS in the Kootenai River began in the late 1960s prior to the construction of Libby Dam. Suspended-sediment samples were collected at several sites along the Kootenai River to quantify sediment transport before and after the construction of Libby Dam. Two long-term daily sediment collection sites were located at the Kootenai River below Libby Dam (USGS 12301933) and at Copeland, Idaho (USGS 12318500). Suspended-sediment samples were collected at the site below Libby Dam from October 1, 1967, to January 31, 1976, and at Copeland from May 26, 1966, to January 2, 1984. Barton (2004) compared the sediment-transport loads before and after the construction of Libby Dam. Median suspended-sediment concentration (SSC) and suspended-sediment loads (SSL) before Libby Dam were about 337 mg/L and 43,400 ton/d. After the construction of Libby Dam, median SSC and SSL decreased to about 2 mg/L and 43 ton/d. Results of suspended-sediment samples collected downstream of the white sturgeon critical habitat at Copeland revealed a 50–75 percent decrease of mean annual sand-sized suspended sediment transported during the spring and early summer after the construction of Libby Dam (Barton, 2004).

In 2007 and 2008, sediment transport data were collected and analyzed at three sites to describe the relations of sediment transport in the critical habitat. Selected sites included the top and lower part of the braided reach and the lower extent of the critical habitat in the meander reach. Suspended-sediment transport curves were developed between concentrations and streamflow to estimate concentrations on a continuous basis, although limitations were noted because of episodic sediment contributions not necessarily associated with high streamflow (Ryan Fosness, U.S. Geological Survey, oral commun., January 2015). Sediment-transport curves for the fines fraction of total suspended sediment were developed as a function of tributary streamflow. Total sediment load in the critical habitat was predominantly fine-grained sediment less than 0.0625 mm that remained in suspension; coarse sand and gravel loads represented less than or equal to 3 percent of the total sediment loads through the critical habitat (Fosness and Williams, 2009).

Holnbeck and Lawlor (2008) collected suspended and bedload sediment data on five Kootenai River tributaries downstream of Libby Dam in the spring of 2008 to quantify tributary sediment contributions—Fisher River, Libby Creek, Parmenter Creek, Ruby Creek, and Yaak River (fig. 1). Streamflow during the Holnbeck and Lawlor (2008) study was considered at the bankfull condition because of an above-average snowpack. Results showed that the sampled tributaries contributed more than 10,000 ton/d combined of both suspended and bedload sediments during the spring of 2008 (Holnbeck and Lawlor, 2008). Though the 2008 sediment transport estimates from the tributaries were likely above average because of the above-average streamflows, the Holnbeck and Lawlor (2008) study showed that the tributaries can contribute a large portion of the sediment in the Kootenai River downstream of Libby Dam.

Sediment Surrogate Technologies

Prior to the study described in this report, continuous records of suspended sediment were estimated for various periods using relations with streamflow at selected sites described in section, "Sediment Data Collection and Analysis." Other sediment surrogate technologies have not been previously evaluated in the Kootenai River. The USGS has traditionally used streamflow as a surrogate to estimate SSC and SSL on the basis of guidelines in Porterfield (1972), Glysson (1987), and Nolan and others (2005). In such studies, a relation is developed between streamflow and SSC or SSL using logarithmic (log) transformations on both variables or plotting on log scales. The relation, which might be linear or non-linear, is called a sediment-transport curve. Uncertainties in sediment-transport curves, including sediment concentrations that differ for the same streamflows on the rising and falling limb of the streamflow hydrograph, have led to the development and evaluation of more direct, in-situ surrogate techniques. Acoustic instruments have shown great promise as sediment-surrogate technologies in rivers. They are tolerant of biological fouling and measure backscatter profiles across a sampling volume rather than at a single point in the river (Gartner and Gray, 2005; Wood, 2014).

Acoustic backscatter measured using fixed-mounted, horizontal-looking acoustic Doppler velocity meters (ADVMs) has been used with success as a surrogate technology for SSC or suspended-solids concentration in the Snake and Clearwater Rivers (Wood and Teasdale, 2013), San Francisco Bay (Gartner, 2004), Florida estuaries (Patino and Byrne, 2004), urban rivers (Landers, 2012), Colorado River (Topping and others, 2006), Hudson River (Wall and others, 2006), and subtropical estuaries in Australia (Chanson and others, 2008). ADVMs transmit pulses of sound at a known frequency, along two or more beams angled to flow, which reflect off sediment in the water (fig. 2). ADVMs are primarily used to measure water velocity using the Doppler principle but also output a return pulse strength indicator, called "backscatter" (Levesque and Oberg, 2012). Although the principal purpose of the backscatter measurement is to assure the quality of velocity data, it also can serve as an indicator of the concentration of sediment in the meter's measurement volume. Backscatter should increase when more particles are present in the water. In sediment surrogate studies previously mentioned, scientists have collected sediment samples from the river while the ADVM is deployed (fig. 2) and related the sediment concentrations to backscatter measurements during sample collection.

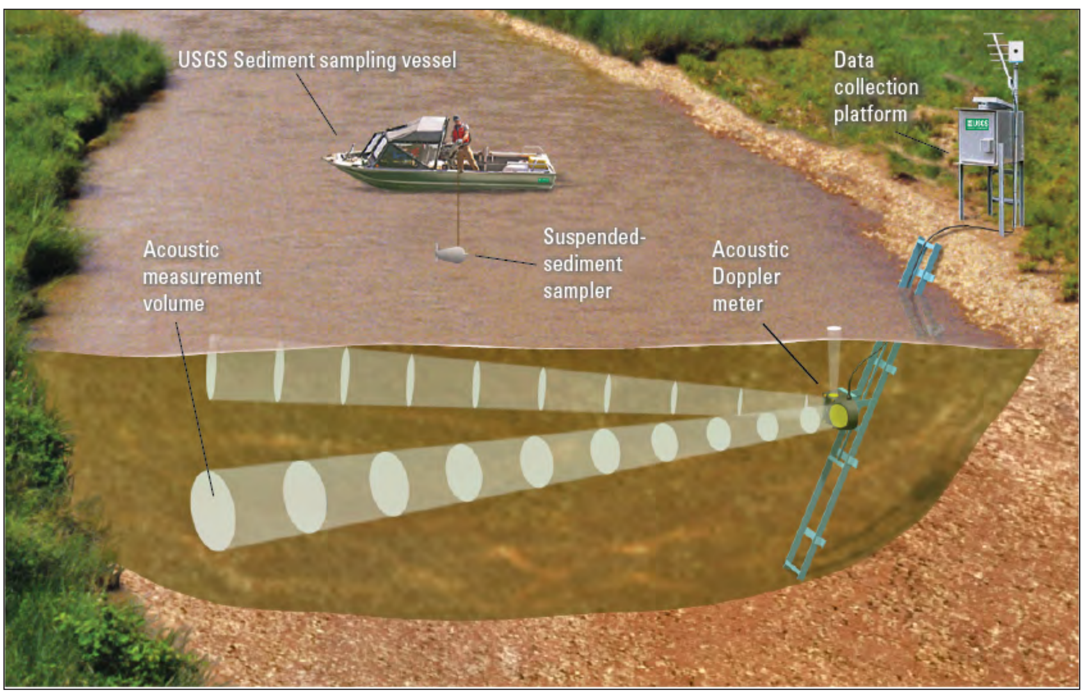


Figure 2. Example of a sediment acoustic surrogate streamgage (adapted from image provided by SonTek® / Xylem and reproduced from Wood, 2014).

Methods

The following sections describe the methods used to collect suspended-sediment and bedload-sediment samples, measure streamflow, and use surrogate methods for the computation of continuous records of SSC and SSL in the Kootenai River in 2011–14.

Field Data Collection

Field data collection in 2011–14 included suspended-sediment and bedload-sediment samples, miscellaneous metadata associated with sediment samples, streamflow measurements, and acoustic surrogate data.

Sediment Sampling

Suspended-sediment samples were collected using the equal-width-increment (EWI) sampling method (U.S. Geological Survey, 2006) with cable-suspended, US D-95 (for one sample set in September 2010) and D-96 depth-integrating, isokinetic water samplers and were analyzed at the USGS Cascades Volcano Observatory Sediment Laboratory in Vancouver, Washington. Samples submitted for analysis were a composite representative of the entire cross section. Sample timing was targeted towards the rising limb, the peak, and the falling limb of the spring freshet or snowmelt runoff hydrograph and sturgeon pulse at each site, but samples were occasionally collected at other times during the year. At each site, 32 EWI suspended-sediment samples were collected during 2011–14 over a wide range in streamflows (table 1) and were analyzed for concentration and percent fines less than 0.0625 mm. Concentrations of fines (particles less than 0.0625 mm; also called washload) and sand (particles greater than or equal to 0.0625 mm) were then calculated for each sample from available analytical data. One suspended-sediment sample was collected in September 2010 but was grouped with data from all other samples collected in 2011–14 because continuous sediment record computation began in 2011. Full particle-size analysis on the sand fraction was performed on EWI samples collected in 2011–13. Additionally, organic content through a loss-on-ignition test was performed on EWI samples collected in 2011–12.

ISCO Model 6712 autosamplers were installed at the Below Moyie and Crossport sites in 2012–13, in an attempt to augment the EWI data set and capture samples during storm events. Using a pump, the autosamplers collected samples from a fixed point about 2–3 ft above the bed at both sites. Two types of samples were collected using the autosamplers (table 1): 13 “grab” samples at each site, composited from two to three 1-L bottles collected at 15-minute increments during EWI sample collection; and 50 samples at each site collected while unattended on the basis of acoustic backscatter triggers set in each site’s datalogger. All samples collected using the autosamplers were analyzed for concentration and percent fines less than 0.0625 mm. The autosampler grab and concurrent EWI sample results were assumed to vary linearly and proportionally, given cross section and sediment transport characteristics. The sample results were used to develop ratings between fixed-point sample concentrations to overall average cross-sectional concentrations, sometimes called development of a “box coefficient rating.” The rating was then used to estimate a synthetic EWI concentration for every unattended autosample concentration.

At the Crossport site, 20 bedload samples were collected in 2011–13 using an Elwha US-ER1 sampler (table 1). The single equal-width-increment (SEWI) method described in Edwards and Glysson (1999) was used, in which samples were collected at 20 evenly spaced verticals in the cross section, constituting an “A” pass sample. The procedure was repeated in the opposite direction to collect another “B” pass sample. Individual samples from each pass were composited into one sample per pass and then submitted for full phi analysis at the USGS Cascades Volcano Observatory Sediment Laboratory. Bedload sampling was targeted towards periods when streamflow was greater than 20,000 ft^3/s and downstream water levels in Kootenay Lake were relatively low, which was expected to generate high bedload transport potential within the study reach resulting from increased stream energy relative to backwater conditions. Some bedload samples were collected when downstream water levels were relatively high, to characterize variability in bedload transport at similar streamflow magnitudes but differing stream energy.

Streamflow Measurement

Stage, velocity, and streamflow data were collected at the Below Moyie and Tribal Hatchery sites according to USGS policies and guidelines in Kennedy (1983), Sauer and Turnipseed (2010), Turnipseed and Sauer (2010), Levesque and Oberg (2012), and Mueller and others (2013) and according to office-specific policies in Wood and others (2014). Streamflow data at the Below Moyie streamgage were computed using stage-discharge rating techniques described in Kennedy (1983). Streamflow data at the Tribal Hatchery streamgage were computed using index-velocity rating techniques described in Levesque and Oberg (2012) because of backwater conditions at the site caused by Kootenay Lake about 73 mi downstream of the streamgage. Streamflow data at the Crossport site were assumed to be the same as the Below Moyie site because no inflows or outflows have been observed in the 2.8-mi river reach between sites. Additionally, discrete streamflow measurements made at the Below Moyie and Crossport sites around the time of sediment sample collection indicated negligible difference between streamflows at the sites.

Table 1. Sediment and streamflow data collected at streamgage and sediment monitoring sites in the Kootenai River, Idaho, water years 2011–14.

[**Abbreviations:** USGS, U.S. Geological Survey; EWI, equal-width-increment; –, not measured or not applicable; mg/L, milligrams per liter; ft^3/s, cubic feet per second; SSC, total suspended-sediment concentration]

Characteristic	Below Moyie site (USGS 12308000)	Crossport site (USGS 12308500)	Tribal Hatchery site (USGS 12310100)	Units
Number of EWI sediment samples collected during study period	32	32	32	number
Number of autosample “grab” sediment samples collected during study period[1]	13	13	–	number
Number of autosample “unattended” sediment samples collected during study period[1]	50	50	–	number
Number of bedload sediment samples collected during study period[2]	–	20	–	number
Mean annual streamflow, period of record[3]	18,030	–	14,750	ft^3/s
Mean annual streamflow, water year 2011	18,800	–	18,200	ft^3/s
Mean annual streamflow, water year 2012	20,300	–	20,300	ft^3/s
Mean annual streamflow, water year 2013	16,900	–	17,000	ft^3/s
Mean annual streamflow, water year 2014	16,000	–	16,000	ft^3/s
Mean suspended-sediment concentration, EWI samples	22	24	29	mg/L
Mean suspended-sediment concentration, autosamples	84	84	–	mg/L
Mean total bedload	–	106	–	tons/day
Range of suspended-sediment concentration, EWI samples	3–113	3–109	3–107	mg/L
Range in percent sands in SSC, EWI samples	9–55	11–56	9–53	percent
Range of suspended-sediment concentration, unattended autosamples	15–222	10–185	–	mg/L
Range in percent sands in SSC, unattended autosamples	17–59	18–74	–	percent
Range of total bedload	–	17–260	–	tons/day
Range of streamflow during sample collection	5,120–56,900	5,170–55,800	4,990–54,800	ft^3/s

[1]Autosampler samples were collected in water years 2012–13 only.

[2]Bedload samples were collected in water years 2011–13 only.

[3]Based on published period of record for streamgage, water years 2010–14 for USGS 12308000, 2003–14 for USGS 12310100.

Sediment Surrogate Monitoring

The ADVMs installed at each site reported acoustic backscatter, which is a byproduct of velocity measurements and is used to quality assure the velocity data. The Below Moyie and Crossport sites were equipped with two SonTek®/Xylem Argonaut-SL ADVMs of two different acoustic frequencies: 1.5 and 3.0 megahertz (MHz) (fig. 3). The acoustic frequencies were selected for this study to maximize sensitivity of backscatter to dominant sediment particle size with relatively low acoustic frequency (1.5 MHz) for the sand-sized fraction in suspension (particle size between 0.0625 and 1 mm) and relatively high acoustic frequency (3.0 MHz) for the fines fraction (particle size less than 0.0625 mm) to minimize errors because of changing particle-size distribution, as described in Gartner (2004) and Topping and others (2006). The frequencies also were selected based on previous experience with acoustic surrogate technologies as described in Landers (2012) and Wood and Teasdale (2013). A 1.5-MHz ADVM was already installed at the Tribal Hatchery site for use in streamflow monitoring using index velocity methods. A second ADVM was not installed at the Tribal Hatchery site because of funding constraints, although the existing ADVM's configuration was altered to optimize measurements for estimating suspended sediment.

The ADVMs at the Below Moyie and Crossport sites were mounted on aluminum slide-track mounts that could be raised and lowered as needed to service equipment. The 1.5- and 3.0-MHz ADVMs measured backscatter in five discrete, equally sized cells in a horizontal sampling volume, at distances of 1.6–51 ft and 1.6–15 ft from the instrument, respectively. The 1.5-MHz ADVM at the Tribal Hatchery site was configured to measure backscatter 1.6–35 ft from the instrument. The sampling volume for each ADVM was selected on the basis of acoustic frequency, abundance of acoustic reflectors along the beam path, and any obstructions in the beam path. Measurement of backscatter in more than five cells is ideal for calculating sediment attenuation (see section, "Acoustic Data Corrections") and the resulting sediment concentration. Data transfer limitations using

Figure 3. U.S. Geological Survey scientist installing and servicing 1.5-megahertz (MHz; left) and 3.0-MHz (right) SonTek®/Xylem acoustic Doppler velocity meters attached to an aluminum slide track mount at the Crossport site (USGS 12308500), Kootenai River, Idaho. (Photograph by Molly Wood, U.S. Geological Survey, August 30, 2010.)

Serial Data Interface-1200 baud rate (SDI-12) protocol, the communication protocol used to transfer data from the ADVMs to the dataloggers at both sites, prevented real-time display of data from more than five cells. As a result, only five cells could be practically used to compute real-time estimates of SSC and SSL using developed surrogate models, which is a goal of the study. All ADVMs deployed at the study sites collected backscatter measurements during 5 minutes out of every 15 minutes at a time offset so that the ADVMs were not measuring backscatter simultaneously, which ensured that one ADVM's acoustic backscatter was not measured and interpreted by the other ADVM.

Direct current voltage converters were installed at each site to maintain constant input power to the ADVMs, about 11.4 volts (V) at the Below Moyie and Crossport sites and 13.2 V at the Tribal Hatchery site. Varying input power should be avoided as it can potentially result in fluctuations in backscatter that have no direct correlation with sediment concentration. The converters were installed between the site's power source and the ADVMs.

Data Analysis

Bedload Transport Curve Development

Bedload was calculated from samples collected in 2011–13 for total sediment (gravel, sand, fines, and organics), total gravel, and total sand in tons per day, according to the SEWI method described in Edwards and Glysson (1999) (eq. 1):

$$Q_b = K \times \left(W_t / T_t\right) \times M_t \,, \tag{1}$$

where

- Q_b is bedload, in tons per day;
- K is a conversion factor calculated as 86,400 seconds per day × 1 ton/907,200 g × 1 ft/N_w, where N_w is the width of the sampler opening (0.667 ft);
- W_t is the width of the stream from which samples are collected, in feet;
- T_t is the total time the sampler rests on the bed, in seconds; and
- M_t is the total mass of the sample, in grams.

Bedload was collected from 20 verticals for each sample, and the sampler rested on the bed for 60 seconds at each vertical, so the total time that the sampler rested on the bed for all samples was 1,200 seconds. Bedload transport curves were developed between log transformations of bedload and streamflow using ordinary least squares regression in TIBCO Spotfire S+® (TIBCO Software Inc., 2008).

Sediment Acoustic Surrogate Analysis

The raw acoustic backscatter data collected from the ADVMs deployed at the study sites were corrected for transmission losses and then related to SSC results from EWI samples. The relations, hereinafter called acoustic surrogate ratings, were then used to calculate continuous estimates of SSC. The continuous estimates of SSC were multiplied by continuous streamflow records to calculate SSL. The sediment acoustic ratings were developed using results of sediment samples collected in 2011–13 and were validated using results of four EWI suspended-sediment samples collected in 2014.

Acoustic Data Corrections

Backscatter data must be range-normalized or corrected for transmission losses through a multi-step process before comparison with EWI sample results. Acoustic backscatter data were corrected for (1) beam spreading, (2) transmission losses owing to absorption by water, and (3) absorption or attenuation by sediment. Methods used for correcting acoustic backscatter data are documented in Wood and Teasdale (2013) and Landers (2012). In summary, corrected acoustic backscatter, ABS_{corr}, is calculated using a form of the sonar equation from Urick (1975) (eq. 2):

$$\mathrm{ABS}_{\mathrm{corr}} = K\left(E - E_r\right) + 20\log_{10}\left(R\right) + 2\alpha_w R + 2\alpha_s R \,, \tag{2}$$

where

- ABS_{corr} is the range-normalized acoustic backscatter (ABS) corrected for two-way transmission losses, in decibels;
- K is a scale factor used to convert uncorrected ABS, in counts to decibels;
- E is the raw amplitude of the uncorrected ABS as reported by the acoustic device, in counts;
- E_r is the received signal strength indicator reference level or instrument noise floor, in counts;
- R is the slant distance along the acoustic beam to the measurement location incorporating beam angle (25 degrees for SonTek®/Xylem ADVMs), in meters;
- α_w is the water absorption coefficient, in decibels per meter; and
- α_s is the sediment attenuation coefficient, in decibels per meter.

The scale factor used to convert uncorrected ABS in counts to decibels typically ranges from 0.35 to 0.55 according to Deines (1999). For SonTek®/Xylem ADVMs, the appropriate value for K when converting ABS from counts to decibels is 0.43 (SonTek/Yellow Springs Instruments, 2009). The term E_r, or instrument noise floor, is specific to the ADVM and deployment location, and is the baseline echo measured by the instrument when no signal is transmitted. Local electronic interferences can affect E_r. E_r was measured automatically by the ADVMs used in this study immediately after a backscatter measurement was made. The term $K(E\text{-}E_r)$ was output from the SonTek®/Xylem ADVMs directly as the signal-to-noise ratio (SNR) in each cell, so this term was used in all calculations because it incorporated actual measurements of the instrument noise floor.

Sediment Acoustic Surrogate Ratings

Mass concentration of suspended sediment was related to acoustic backscatter using equation 3 in exponential form:

$$\mathrm{SSC} = \left[10^{\left(\beta_0 + (\beta_1 \mathrm{ABS_{corr}}) + (\beta_2 EVi) + \ldots + (\beta n EVn)\right)}\right] \times \mathrm{BCF}\,, \quad (3)$$

where

- SSC is suspended-sediment concentration, in milligrams per liter;
- β_0 is the equation intercept;
- β_1 is the regression coefficient corresponding to $\mathrm{ABS_{corr}}$;
- $\mathrm{ABS_{corr}}$ is the range-normalized acoustic backscatter (ABS) corrected for two-way transmission losses, in decibels;
- *EVi* through *EVn* are other explanatory variables used in the regression, and β_2 through β_n are the corresponding regression coefficients. The regression coefficients are determined by regressing mass concentration measurements of suspended sediment with measurements of $\mathrm{ABS_{corr}}$ and other explanatory variables during sample collection; and
- BCF is Duan's (1983) bias correction factor, also described in Wood and Teasdale (2013).

Separate ratings were developed between acoustic surrogate variables and SSC, sand concentration, and fines concentration using ordinary least squares regression techniques (Helsel and Hirsch, 2002) for the Crossport and Tribal Hatchery sites in TIBCO Spotfire S+ statistical software (TIBCO Software Inc., 2008). Weighted least squares regression techniques (Helsel and Hirsch, 2002) were used to develop sediment acoustic ratings for the Below Moyie site because the data set included both regular EWI samples collected using standard USGS procedures and EWI estimates generated using a box coefficient rating (see section, "Sediment Sampling"). The EWI estimates generated using a box coefficient rating were considered to have a higher uncertainty than the regular EWI samples because they were themselves generated using a least squares regression. As a result, regular EWI samples were given a weight of "1" (full weight) and EWI estimates generated using the box coefficient rating were given a weight equal to the coefficient of determination of the respective box coefficient rating (the poorer the relation, the lower the weight). The weighted least square regression was then performed on the weighted sample concentrations at the Below Moyie site using TIBCO Spotfire S+ statistical software (TIBCO Software Inc., 2008).

Additional explanatory variables that were evaluated included the sediment attenuation coefficient (α_s in eq. 2), a sediment attenuation coefficient ratio calculated using data from both frequency ADVMs, stream velocity measured by the 1.5-MHz ADVM, and a term called "Libby Dam Ratio" (LDR) that represented the relative contribution of streamflow passing each site from tributaries downstream of Libby Dam (eq. 4):

$$\mathrm{LDR} = Q_{\mathrm{site}} \,/\, Q_{12301933}\,, \quad (4)$$

where

- LDR is the Libby Dam Ratio, a dimensionless number;
- Q_{site} is the unit value 15-minute streamflow at the study site, either Below Moyie, Crossport, or Tribal Hatchery, in cubic feet per second; and
- $Q_{12301933}$ is the unit value 15-minute streamflow in the Kootenai River below Libby Dam (USGS 12301933), in cubic feet per second.

Lag times of 8 and 12 hours between streamflows measured downstream of Libby Dam and at the Below Moyie/Crossport and Tribal Hatchery sites, respectively, were evaluated and used to calculate a $\mathrm{LDR_{lagged}}$ term. Log transformations were performed on SSC, stream velocity, LDR, and $\mathrm{LDR_{lagged}}$ terms prior to their evaluation in the regression models. Various transformations were evaluated, including the log (base 10), natural log, square root, cube root, reciprocal root, and reciprocal, as described in Helsel and Hirsch (2002). Additionally, the decision on the "best fit" for transformation was made considering evaluations completed on similar datasets described in Wood and Teasdale (2013). Use of the log transformation produced the best fit and most linear relations of other evaluated transformations. Acoustic backscatter data were already reported in a log-based scale and did not require a transformation. The best regression models were selected for the ratings on the basis of visual fit with measured data, the coefficient of determination, standard error, p-values, and residuals plots. Throughout the report, the term "significant" means that an explanatory variable or rating was statistically significant at an alpha level of 0.10.

Prediction intervals of 95 percent were approximated for the selected acoustic surrogate ratings according to a simplified equation in Rasmussen and others (2009), as adapted for this study (eq. 5):

$$\left[10^{\left(\log y-\left(t_{\left(\frac{\alpha}{2},n-p\right)}\mathrm{SE}\right)\right)}\right]\times \mathrm{BCF}\leq y\leq\left[10^{\left(\log y+\left(t_{\left(\frac{\alpha}{2},n-p\right)}\mathrm{SE}\right)\right)}\right]\times \mathrm{BCF}, \quad (5)$$

where

y	is the value of the response variable, or sediment concentration;
SE	is the standard error of the model residuals, in log space;
$t_{(\alpha/2,n-p)}$	is the value of the Student's t-distribution at probability $\alpha/2$ and degrees of freedom $n-p$; and
BCF	is Duan's (1983) bias correction factor, also described in Helsel and Hirsch (2002) and Wood and Teasdale (2013).

Calculation and use of the variance-covariance matrix may provide more exact estimates of prediction intervals in the future. The decision to use the simplified approach shown in equation 5 was made because of the computational challenges associated with the variance-covariance matrix at the time of model development and because the simplified and variance-covariance matrix methods have yielded similar results in other studies using turbidity as a sediment surrogate (Patrick Rasmussen, U.S. Geological Survey, written commun., 2013).

The SSL was calculated for each time step using equation 6 adapted from Porterfield (1972):

$$\mathrm{SSL} = Q\times \mathrm{SSC}\times \Delta t\times c\ , \quad (6)$$

where

SSL	is the suspended-sediment load, in tons per time step;
Q	is the instantaneous (15-minute) streamflow, in cubic feet per second;
SSC	is the suspended-sediment concentration, in milligrams per liter;
Δt	is the time increment since the last reading, usually 15 minutes but sometimes longer in the case of missing data, in minutes; and
c	is a factor for converting Q (ft^3/s), SSC (mg/L), and (minutes) to SSL (tons), or 1.873E-06.

The SSLs for each time step were then summed by month and year.

Sediment Streamflow Surrogate Analysis

As a comparison to SSL computed using the acoustic surrogate ratings, surrogate ratings also were developed using streamflow, which traditionally has been used to estimate SSL on a continuous basis in rivers. For this study, loads for total suspended sediment, sands, and fines were estimated using the USGS Load Estimator (LOADEST) program (Runkel and others, 2004; Runkel, 2013), as adapted for the R programming language. The LOADEST modeling program is based on a rating-curve method (Cohn and others, 1989, 1992; Crawford, 1991) that uses linear regression to estimate constituent loads using several explanatory variables related to streamflow and time. This type of rating has been used to estimate constituent concentrations for periods when sample data were not available (Gilroy and others, 1990) and to estimate loads of water-quality constituents from drainage basins (Goolsby and others, 1999). The LOADEST program develops regression models for loads directly, not concentrations, so the resulting model fit statistics cannot be directly compared with those from the acoustic surrogate ratings.

The basic model form and explanatory variables evaluated for the LOADEST regressions developed for this study are shown in equation 7:

$$\begin{aligned}\ln L = I + a(\ln Q) + b(\ln Q^2) + c\left[\sin\left(2\pi T\right)\right] \\ + d\left[\cos\left(2\pi T\right)\right] + e\left(dQ_k\right) + f\left(\mathrm{LDR}\right) + \varepsilon\end{aligned}\ , \quad (7)$$

where

L	is the constituent load, in pounds per day;
I	is the regression intercept;
Q	is streamflow, in cubic feet per second;
T	is the centered decimal time from the beginning of the calibration period, in years;
dQ_k	is the term describing streamflow variability, as defined in equation 8;
LDR	is the Libby Dam Ratio term used to represent streamflow contributions from tributaries between Libby Dam and the study area as defined in equation 4;
sin ($2\pi T$), cos ($2\pi T$)	are terms representing seasonality;
a, b, c, d, e, f	are regression coefficients that remain constant over time; and
ε	is the unaccounted error associated with the regression.

The explanatory variable dQ_k was evaluated to represent streamflow variability or hysteresis and is described in Garrett (2012). Hysteresis occurs when the value of a physical property (constituent concentration or load) changes at a different rate than the effect assumed to be causing it (streamflow). Use of a streamflow hysteresis term might eliminate the need to develop a different regression between streamflow and load depending on whether samples were collected on the rising or the falling limb of the hydrograph. The streamflow hysteresis term was defined as the difference between mean streamflow (Q) on day i and the mean streamflow of the previous k days, given as equation 8 but described in more detail in Garrett (2012):

$$dQ_k = \sum_{j=i-k}^{i-1} \frac{\ln Q_j}{k}, \tag{8}$$

where

Q	is mean streamflow, in cubic feet per second;
d	indicates a difference is taken in streamflows between time step k;
k	is the time step, in days; and
i,j	are days evaluated in the hysteresis analysis.

For this study, a 1-day "k" time step (dQ_1) was evaluated to describe the effects of hysteresis.

Explanatory variables related to long-term trends over time were not evaluated in the streamflow surrogate ratings because of the short duration of the study. The LDR term (eq. 4) described in section, "Sediment Acoustic Surrogate Analysis," was evaluated as an explanatory variable in the LOADEST model analysis. The LDR term was calculated in various ways to determine the best fit for the LOADEST models: use of unit value (UV) (15-minute) with and without lag times of 8–11 hours (Below Moyie/Crossport sites) and 12 hours (Tribal Hatchery site) and daily mean streamflows.

As with the sediment acoustic ratings, all available data from samples collected in 2011–13 were used to calibrate the regression models, and data from samples collected in 2014 were used to validate the selected models. For each rating, explanatory variables in the regression equation were selected on the basis of visual fit with measured data, standard error, p-values, residuals plots, and the Akaike Information Criteria (AIC; Akaike, 1981). Evaluation of ratings using the AIC is intended to achieve a good compromise between using as many explanatory variables as possible to explain the variance in SSL while minimizing the standard error of the resulting estimates. Estimates of the daily constituent SSL for each site were computed using the selected rating and daily mean streamflow. Bias introduced by conversion of the logarithm of SSL into estimates of actual SSL was corrected using the Bradu-Mundlak method (Bradu and Mundlak, 1970; Cohn and others, 1989; Crawford, 1991). The Bradu-Mundlak bias correction method assumes that model residuals are normally distributed (Helsel and Hirsch, 2002). The Duan bias correction method, used in the sediment acoustic surrogate ratings, does not require the residuals to be normally distributed and would have been a preferable approach if the Bradu-Mundlak method was not automatically built into the LOADEST program. Overall, however, the two methods are expected to produce similar results when the residuals are normally distributed, which was evaluated and verified in selection of the final LOADEST models for this study.

Streamflow and Sediment Transport Patterns

Streamflow Patterns

The USGS streamgage Kootenai River at Leonia (USGS 12305000), hereinafter called Leonia, is about 20 mi upstream of the study area on the Idaho and Montana border (fig. 1). Leonia is the closest streamgage to the study area with a long period of record (extending back to 1928), and was used to compare streamflows measured during the study period (2011–14) to streamflows measured during the regulated "Libby Dam era" up to the study period (1975–2010) and the unregulated "pre-Libby Dam era" (1929–71). Mean annual streamflow in the pre-Libby Dam era was about 14,000 ft^3/s. Mean annual streamflow at Leonia in the Libby Dam era was about 13,300 ft^3/s, and increased about 24 percent to 16,500 ft^3/s during the study period. Mean annual streamflow in 2012 at Leonia was the 7th largest mean annual streamflow, and the study period had the 4th largest, 4-year mean annual streamflow in the period of record. Streamflows at Leonia in spring 2012 were especially high relative to average Libby Dam era conditions and exceeded 40,000 ft^3/s for nearly 2 months.

Mean monthly streamflow at Leonia in the Libby Dam era up to the study period (1975–2010) was bimodal with two peaks of nearly equal magnitude occurring once in December (17,700 ft^3/s) and again in June (18,300 ft^3/s) without a well-defined spring freshet. Low streamflow occurred at Leonia during late spring and early autumn in the Libby Dam era with mean monthly streamflows ranging from about 8,430 to about 10,100 ft^3/s. During the study period, mean monthly streamflow was again bimodal; however, the spring freshet streamflow (32,100 ft^3/s) was about 75 percent more than the mean streamflow in December (18,300 ft^3/s) in the study period and 75 percent more than the mean streamflow in June in the Libby Dam era prior to the study period. Mean monthly streamflow in the autumn during the study period was about 44 percent less than the low streamflow period for the Libby Dam era prior to the study period. Overall, above-average precipitation during the study period resulted in above-average mean annual streamflow; additionally, VARQ operations at Libby Dam resulted in generally higher spring streamflow and lower autumn streamflow compared to other years in the Libby Dam era.

Mean annual streamflow in the study area averaged about 18,000 ft^3/s at the Below Moyie and Tribal Hatchery sites in 2011–14 (table 1). Streamflows downstream of Libby Dam (USGS 12301933) in 2011–14 averaged about 13,100 ft^3/s. The difference in streamflow between the two sites was largely the result of tributary contributions between Libby Dam and the study area. Streamflow in the study area in 2011–14 exceeded the long-term (2003–14), mean annual streamflow computed at the Tribal Hatchery site, most notably by 38 percent in 2012. Streamflow generally was highest in May through July during the spring freshet and sturgeon pulse compared to other months during 2011–14. The largest differences between the streamflows downstream of Libby Dam and in the study area were generally in May (about 16,000 ft^3/s different), corresponding to highest streamflows contributed by tributaries downstream of Libby Dam. Streamflow generally was lowest in October compared to other months during 2011–14, averaging about 5,790 ft^3/s in the study area and 4,570 ft^3/s downstream of Libby Dam.

Sediment Transport Patterns

Sediment transport in the Kootenai River varied during 2011–14 based on the duration, magnitude, timing, and source (Libby Dam releases or from tributaries downstream of Libby Dam) of the streamflow. Results of sediment samples collected during this study and used to characterize sediment transport are provided in appendix A.

Suspended Sediment

Highest SSC and fines concentrations in sediment samples were measured soon after rain-on-snow events increased streamflows and sediment contributions in tributary watersheds between Libby Dam and the study area. Highest sand concentrations in sediment samples were measured when total streamflow in the study area was high, typically but not always associated with releases from Libby Dam (fig. 4). Streamflows released from Libby Dam were anecdotally observed to be predominantly clear water and were generally assumed to have low sediment concentrations, so the source of sand measured at the study sites during high streamflows was expected to be from (1) upstream tributaries, immediately transported to the study area; (2) upstream tributaries, deposited in the river upstream of the study area, and re-suspended and transported during high streamflows; (3) streambank erosion; or (4) a combination of each. Suspended sand concentrations measured in samples collected at the Below Moyie site were relatively low until streamflows exceeded about 25,000 ft^3/s (fig. 4), which typically corresponds to increased streamflow releases from Libby Dam or a combination of increases in tributary inflows and Libby Dam releases but not typically because of increases in tributary inflows alone. This pattern was similar among all study sites.

The highest SSC results (table 1; fig. 4) were measured in samples collected in late April 2012 during a rain-on-snow event that resulted in high streamflow (40,000–50,000+ ft^3/s) at the study sites composed primarily of contributions from upstream tributaries (fig. 4). Samples were collected using autosamplers at the Below Moyie and Crossport sites during the event, which showed that SSC and sand concentrations peaked just before the peak in streamflow.

For a given sample set collected on the same or subsequent days, SSC generally increased among study sites from upstream to downstream (table 2). In many cases, little difference was present among SSC results at sites. In fact, the coefficient of variance (COV), or standard deviation divided by the average concentration among sites, in SSC was only about 4 percent at SSCs higher than 40 mg/L (table 2). Sand concentrations were more variable than SSC among sites (36 percent COV at sand concentrations greater than 10 mg/L) but were low overall. Similar to SSC, sand concentrations generally increased among study sites from upstream to downstream. A few exceptions to the increasing downstream trend in sand concentrations were the sample sets collected in June 2012, which showed a general decrease in sand concentrations between the upstream and downstream sites. The June 2012 samples were collected during a period of high streamflow releases from Libby Dam (the sturgeon pulse) and high backwater extent at the Tribal Hatchery site resulting from high Kootenay Lake water surface elevations, which probably resulted in sand dropping out of suspension upstream of the Tribal Hatchery. Throughout the year, comparisons of suspended-sediment data among sites indicated that small differences in sediment were probably because of sampling variability and timing (the same “slug” of sediment may not have been measured at all sites on the same day), local hydraulic conditions, and localized sources such as overland runoff, small tributaries, and streambank erosion between sites.

On average, the relative percentage of SSC in EWI samples collected in 2011–14 and composed of fines was 73, 71, and 70 percent at the Below Moyie, Crossport, and Tribal Hatchery sites, respectively. Above average fines concentrations were measured in samples collected at the Below Moyie and Crossport sites when LDR was high, meaning that streamflow passing the study sites when these samples were collected consisted primarily of tributary inflows and again indicated that the tributaries were the source of the fines.

Suspended-sediment samples collected in 2011–13 were analyzed for full particle-size analysis on the sand fraction. The results showed that the relative percentage of SSC in EWI samples composed of very fine and fine sands increased slightly among sites from upstream (Below Moyie site) to downstream (Tribal Hatchery site; fig. 5). In general, concentrations of coarse sand were very low or negligible at high values of LDR, indicating that sand contributed by the tributaries was not immediately transported to the study area.

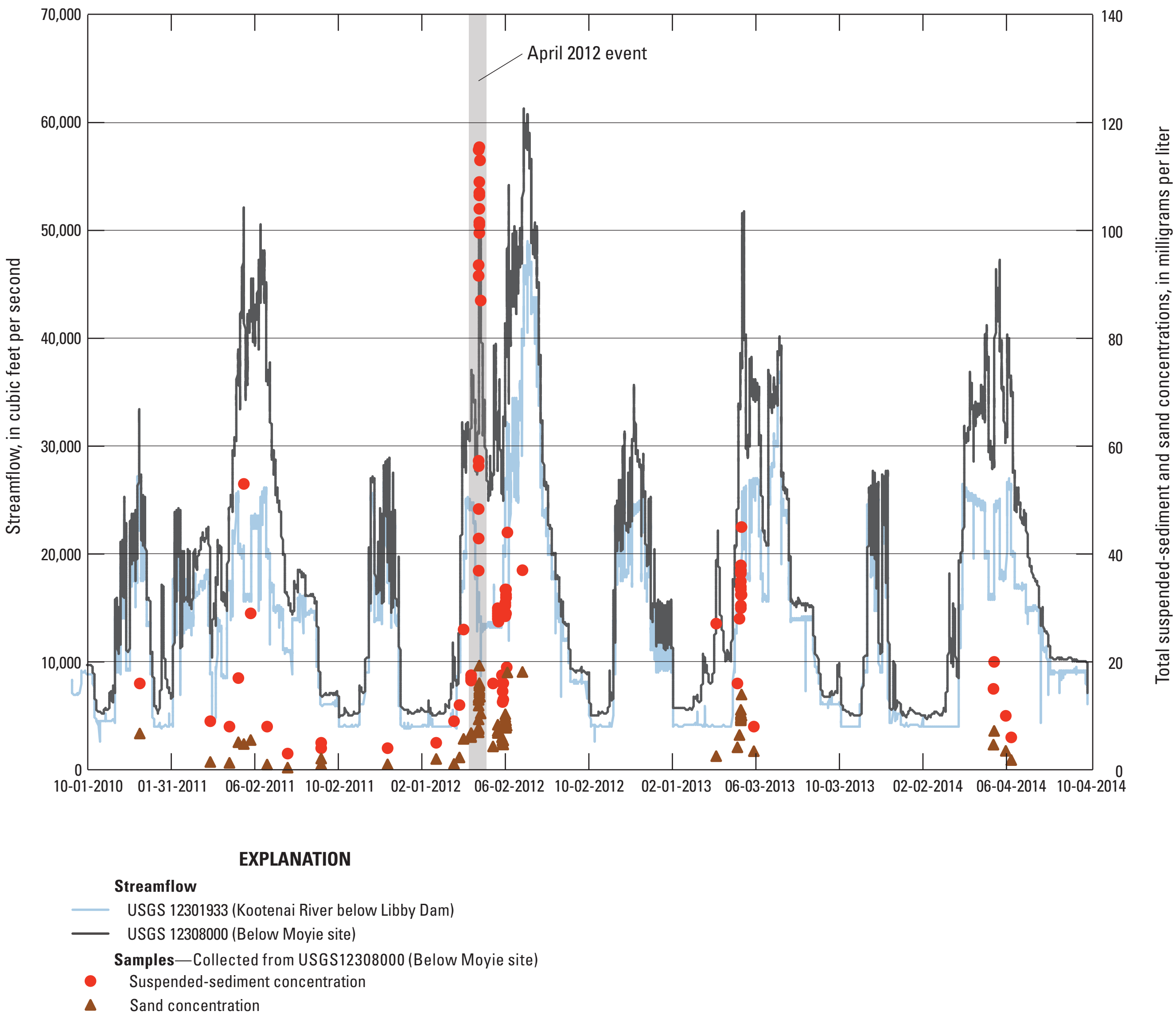


Figure 4. Streamflow measured at the Kootenai River below Libby Dam near Libby, Montana (USGS 12301933) and Below Moyie site (USGS 12308000) and total suspended-sediment and sand concentrations measured in equal-width-increment samples collected at the Below Moyie site, water years 2011–14.

Coarse and fine sand concentrations were negligible until streamflows entering the study area exceeded about 43,000 ft^3/s but were still low overall. Sand concentrations and proportions of sand in samples collected at the Tribal Hatchery site generally were higher than samples collected at the other sites (fig. 5, table 2). As mentioned in section, "Description of Study Area," the source of this sand may be sand transported in the river that was deposited on the streambed in the backwater zone caused by Kootenay Lake and was subsequently available for re-suspension during high streamflows. Additionally, some sand likely was contributed to the channel and measured at the Tribal Hatchery site because of documented bank erosion in the braided reach (Kootenai Tribe of Idaho, 2009). Concentrations of very fine and fine sands at the Tribal Hatchery site were fairly consistent at streamflows higher than 20,000–30,000 ft^3/s, but concentrations of medium and coarse sand were particularly small compared to the other sites probably because they dropped out of suspension in the backwater zone extending about 3 river miles upstream.

Organic matter content was relatively low (0–8 mg/L) at all sites among the samples analyzed using the loss-on-ignition test. On average, organic matter was 10–16 percent of total SSC among sites. The highest organic matter content was measured in samples collected during the 2011 winter FRM streamflows and 2012 spring snowmelt runoff. Although organic matter content was not included in the analysis and reporting of SSC, it may have contributed to uncertainties in the surrogate ratings as described in section, "Evaluation of Sediment Surrogate Ratings."

Table 2. Total suspended-sediment and sand concentrations measured in samples collected from sediment monitoring sites in the Kootenai River, Idaho, water years 2011–14.

[**Abbreviations:** USGS, U.S. Geological Survey; mg/L, milligrams per liter; >, greater than; –, not measured or not applicable]

Sample date	Total suspended-sediment concentration (SSC) (mg/L)			Suspended-sand concentration (mg/L)			Coefficient of variation (COV) (percent)	
	Below Moyie site (USGS 12308000)	Crossport site (USGS 12308500)	Tribal Hatchery site (USGS 12310100)	Below Moyie site (USGS 12308000)	Crossport site (USGS 12308500)	Tribal Hatchery site (USGS 12310100)	Total suspended-sediment concentration	Suspended-sand concentration
[1]09-13-10	3	3	3	1	2	1	–	36
12-14–16-10	16	24	30	10	7	6	30	26
03-29-11	9	7	16	1	1	4	44	87
04-26-11	8	10	–[2]	2	1	–[2]	16	28
05-09-11	17	21	35	7	5	17	39	69
05-17-11	53	60	63	7	5	9	9	34
05-27-11	29	31	30	5	6	5	3	2
06-20-11	8	9	10	2	1	2	11	34
07-20-11	3	10	3	6	0.4	0.4	76	140
09-07-11	5	5	5	1	1	0.5	–	42
12-13-11	4	4	12	2	1	5	69	87
02-22-12	5	5	10	2	2	2	43	11
03-19-12	9	6	14	1	1	2	42	54
03-27-12	12	16	48	5	2	23	78	111
04-02-12	26	26	35	6	6	11	18	36
04-13-12	17	19	35	8	7	18	42	54
04-26-12	113	109	107	14	14	14	3	2
04-27-12	87	86	87	9	10	13	1	17
[3]05-15-12	16	18	24	6	4	9	22	34
05-30-12	13	13	14	4	5	4	4	15
06-04-12	19	20	21	9	8	8	5	8
06-05-12	44	51	47	21	18	16	7	14
06-27-12	37	33	31	13	18	12	9	24
04-06-13	27	49	36	6	3	7	29	45
05-07-13	16	19	32	6	4	10	38	43
05-10-13	28	29	37	7	6	11	16	32
05-13-13	45	43	48	12	14	16	6	12
05-31-13	8	8	9	3	3	4	7	6
05-16-14	15	16	20	4	5	8	16	36
05-17-14	20	27	30	12	7	13	20	27
06-03-14	10	11	13	5	4	5	13	21
06-11-14	6	5	7	1	2	2	17	26
					Average COV overall		23	38
					Average COV, SSC > 40 mg/L		4	–
					Average COV, Sand > 10 mg/L		–	36

[1]Sample collected on September 13, 2010, was collected in water year 2010, but it was grouped with all other data collected in water years 2011–14 because continuous sediment record computation did not begin until water year 2011.

[2]Sample result flagged as erroneous due to suspicion that sampler hit a sand dune and entrained bed sediment in suspended sample.

[3]Samples collected at a condition considered to be "bankfull" streamflow, when Kootenai River at Tribal Hatchery (USGS 12310100) streamflow was about 30,000 cubic feet per second and Kootenai River at Porthill (USGS 12322000) water-surface elevation was about 1,754 feet.

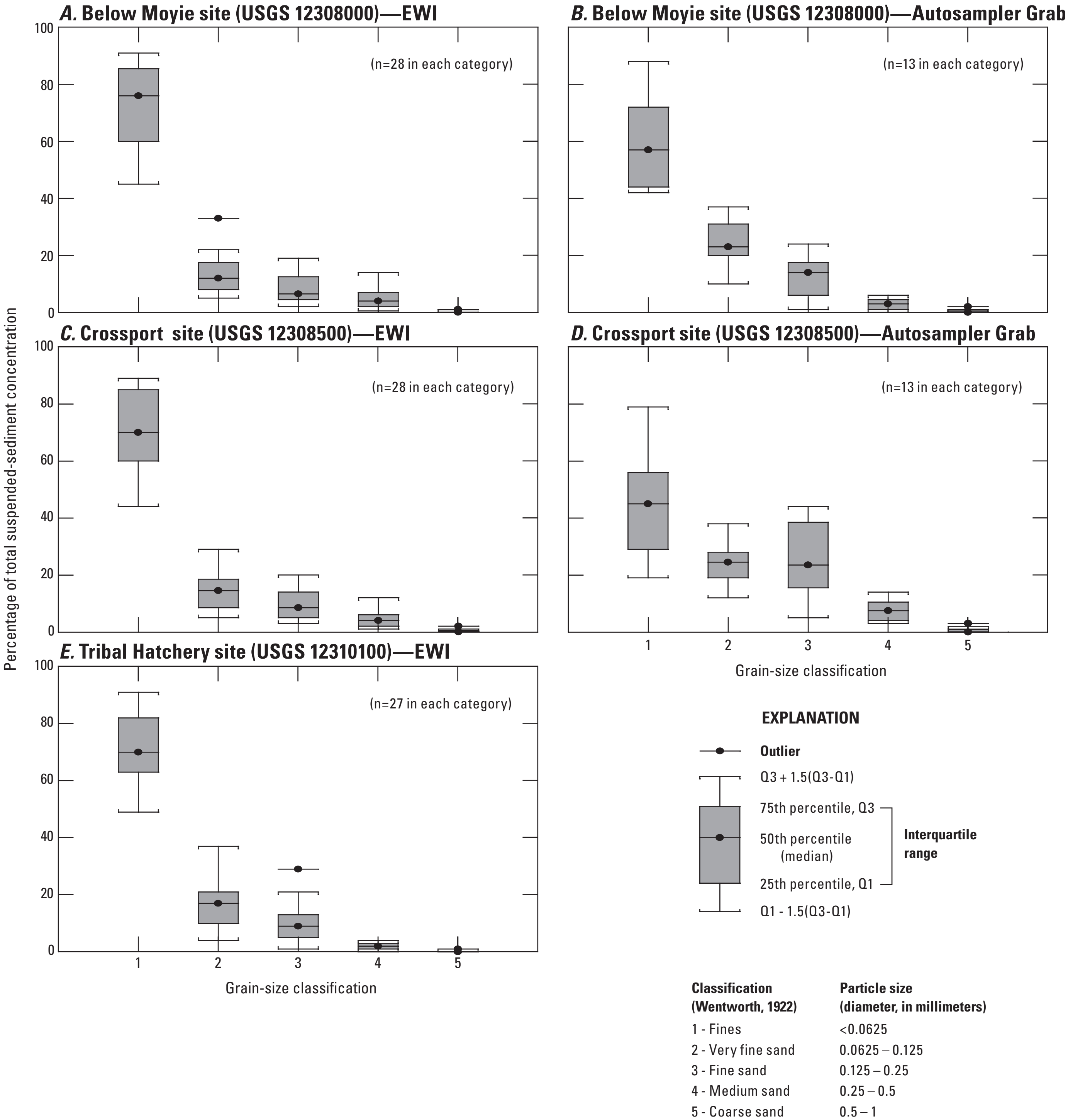


Figure 5. Percentage of total suspended-sediment concentration consisting of fines and sand particle-size classifications for samples collected at sediment monitoring sites in the Kootenai River, Idaho, water years 2011–13. (EWI, equal-width-increment)

Efforts to develop box coefficient ratings for estimating EWI concentrations using grab samples collected from the autosampler at the Below Moyie and Crossport sites were met with mixed results. As expected, the relative proportion of sands in total SSC were higher in the grab samples collected from the autosampler than in the EWI samples (fig. 5) because sand concentrations generally increase low in the water column, near the autosampler intakes. Particle-size distributions and SSC in the autosampler grab samples were more variable among samples at the Crossport site than at the Below Moyie site. As a result, the developed ratings between autosampler grab and EWI SSC, fine, and sand concentrations were much better for the Below Moyie site than for the Crossport site (table 3). In fact, the box coefficient rating to estimate EWI sand concentrations at the Crossport site was not statistically significant ($p>0.10$).

Results from suspended-sediment sampling at the Kootenai River study sites were compared to results of samples collected during comparative conditions in other rivers in the Western United States. Holnbeck (2005) developed regression and envelope lines for SSL at bankfull streamflow in relation to drainage area using suspended-sediment transport data for seven rivers with minimal regulation in the northern Rocky Mountains. The envelope line represents the upper bound of data for other selected sites in the northern Rocky Mountains. SSL for other rivers, including the Yellowstone River, which was the subject of Holnbeck's (2005) study, were plotted in relation to the regression and envelope lines for comparison of the variability of sediment transport characteristics. Bankfull streamflow was presented in Holnbeck (2005) as similar to the effective streamflow, or the streamflow that transports more sediment than any other streamflow, and corresponded roughly to a streamflow with a 50 percent annual exceedance probability or 2-year recurrence interval. For the Kootenai River, the bankfull streamflow condition has been defined as 30,000 ft^3/s at the Tribal Hatchery site and a water-surface elevation of 1,754 ft at the Kootenai River at Porthill (USGS 12322000) (Kootenai Tribe of Idaho, 2009). Samples were collected on the Kootenai River on one date when the bankfull conditions were met—May 15, 2012. Results of the SSL for all three sites on May 15, 2012, in relation to a portion of the Kootenai River drainage area downstream of Libby Dam (3,950 mi^2; fig. 6) show that SSL in the Kootenai River was substantially lower than estimated by the Holnbeck (2005) SSL regression and envelope lines and was similar to sites with drainage areas in the range 40–100 mi^2. The results further indicate that upstream watershed regulation has substantially reduced the incoming SSL to the Kootenai River relative to historical, unregulated conditions.

Table 3. Box coefficient ratings developed between equal-width-increment and autosampler grab samples collected at the time of equal-width-increment samples at sediment monitoring sites in the Kootenai River, Idaho, water years 2012–13.

[**Abbreviations:** USGS, U.S. Geological Survey; EWI, equal-width-increment; R^2, coefficient of determination; mg/L, milligrams per liter; SSC, total suspended-sediment concentration; ASG, autosampler grab]

Sediment type	Number of samples used for rating	Rating	R^2	Residual standard error (mg/L)
Below Moyie site (USGS 12308000)				
Total suspended-sediment concentration	13	EWI SSC = 0.497×ASG SSC + 5.105	0.89	11
Sand concentration	13	EWI Sand = 0.237×ASG Sand + 2.997	0.63	3.5
Fines concentration	13	EWI Fines = 0.624×ASG Fines + 3.560	0.95	6.3
Crossport site (USGS 12308500)				
Total suspended-sediment concentration	13	EWI SSC = 0.197×ASG SSC + 16.93	0.35	25
Sand concentration	13	[1]EWI Sand = 0.0218×ASG Sand + 7.715	0.086	4.8
Fines concentration	13	EWI Fines = 0.760×ASG Fines - 1.836	0.8	13

[1]Relation was not statistically significant at an α level of 0.10.

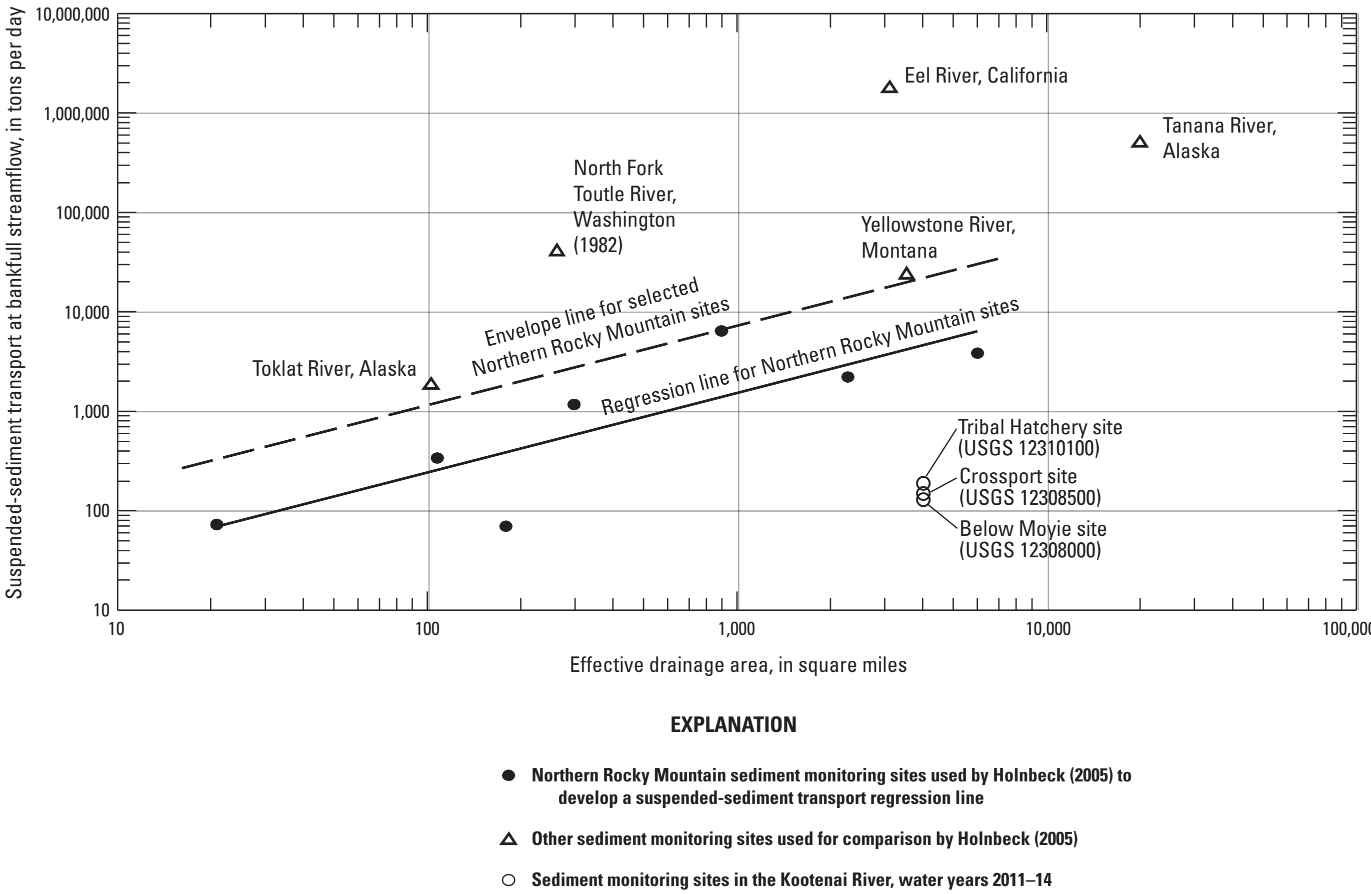
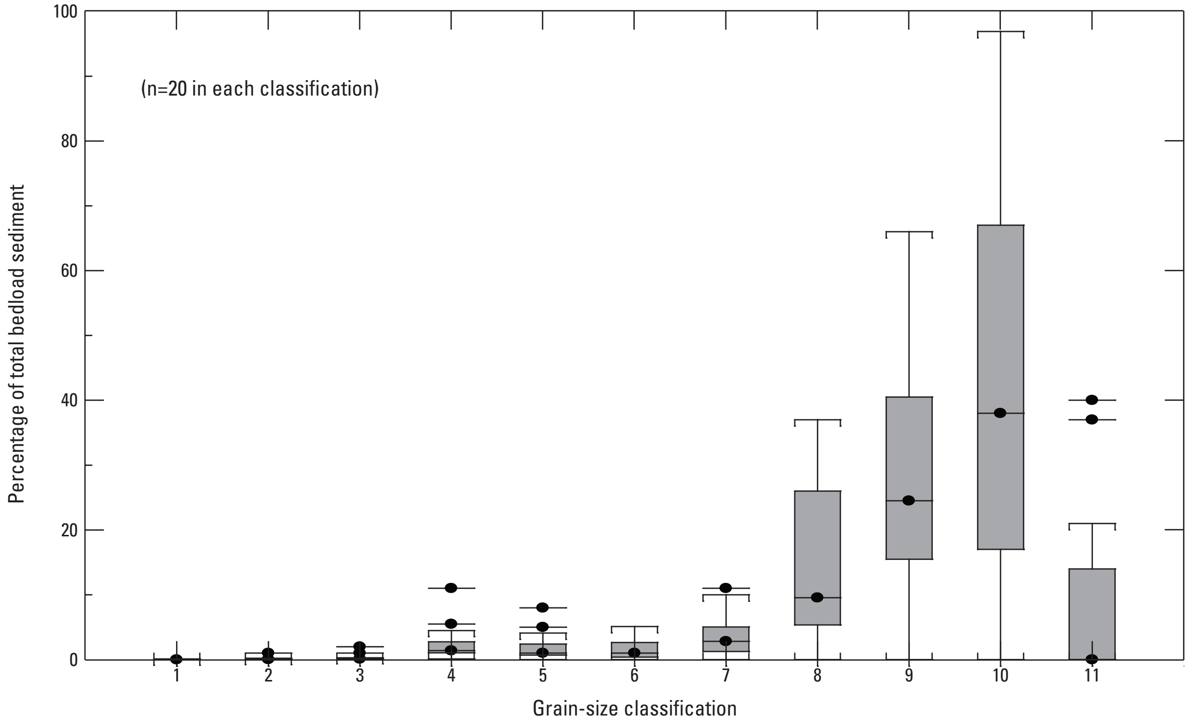


Figure 6. Suspended-sediment transport at bankfull streamflow for selected sites in the Western United States and sediment monitoring sites in the Kootenai River, Idaho. Base data and modified figure from Holnbeck, 2005. The drainage area shown for the Kootenai River is the part considered relatively “unregulated”, downstream of Libby Dam.

Bedload Sediment

Bedload was about 5 percent of the total sediment load measured in samples collected in 2011–13 at the Crossport site and was positively correlated with SSL and streamflow. Bedload contained 95 percent gravel and 4 percent sand on average among all samples. The remaining 1 percent of total bedload included organic material and fines. Most gravel bedload was in the coarse (16–32 mm) and very coarse (32–63 mm) gravel size classifications in the Wentworth (1922) scale, and most sand bedload was in the coarse (0.5–1 mm) sand size classification (fig. 7). The percentage of total bedload sediment in the very fine to medium sand classifications is included in figure 7; however, because the mesh size of the bedload sampler bag was 0.5 mm, particles less than 0.5 mm in the bedload samples were assumed to be present because of occlusion of the mesh opening or because smaller particles were attached to larger sediment particles. Bedload transport curves, or regressions between log streamflow and log total, gravel, and sand bedload, were scattered but statistically significant and positively correlated (fig. 8). A relation also was developed between total bedload and downstream gage height at the Tribal Hatchery site, to determine whether low water levels downstream resulted in high bedload because of high water-surface slope and associated energy. In fact, the opposite seemed true for total bedload, although the relation was very scattered (fig. 9). No significant pattern was noted between sand bedload and downstream water level, but again, sand bedload was low.



EXPLANATION

Abbreviation	Classification (Wentworth, 1922)	Particle size (diameter, in millimeters)
1 - VFS	Very fine sand	0.0625–0.125
2 - FS	Fine sand	0.125–0.25
3 - MS	Medium sand	0.25–0.5
4 - CS	Coarse sand	0.5–1
5 - VCS	Very coarse sand	1–2
6 - VFG	Very fine gravel	2–4
7 - FG	Fine gravel	4–8
8 - MG	Medium gravel	8–16
9 - CG	Coarse gravel	16–32
10 - VCG	Very coarse gravel	32–63
11 - COB	Cobble	63–128

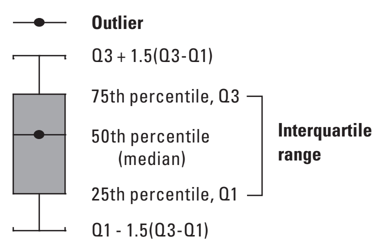


Figure 7. Percentage of total bedload sediment in particle-size classifications for bedload samples collected at the Crossport site (USGS 12308500) in the Kootenai River, Idaho, water years 2011–13.

A perceived decrease in stream energy as backwater extent increases at the Tribal Hatchery site did not necessarily affect bedload transport at the Crossport site; however, hydraulic modeling of the reach indicates that the backwater zone would not typically extend all the way to the Crossport site until streamflow exceeds 50,000 ft^3/s (Mitch Price, River Design Group, Inc., written commun., 2015). Bedload at the Crossport site on dates sampled appeared to be primarily driven by streamflow magnitude, but a future analysis of bedload transport might include a more thorough investigation of the role of energy grade slope and shear stress. The highest streamflows and bedload transport generally corresponded with periods in late May and early June, when backwater extent and associated water levels at the Tribal Hatchery site were high. Percentage differences between results from "A" and "B" pass bedload samples varied greatly, ranging between 0–166 percent. The differences were probably owing to the episodic pulse nature of bedload transport, which has been observed through videos of bedload transport near the Crossport site (http://gallery.usgs.gov/videos/290).

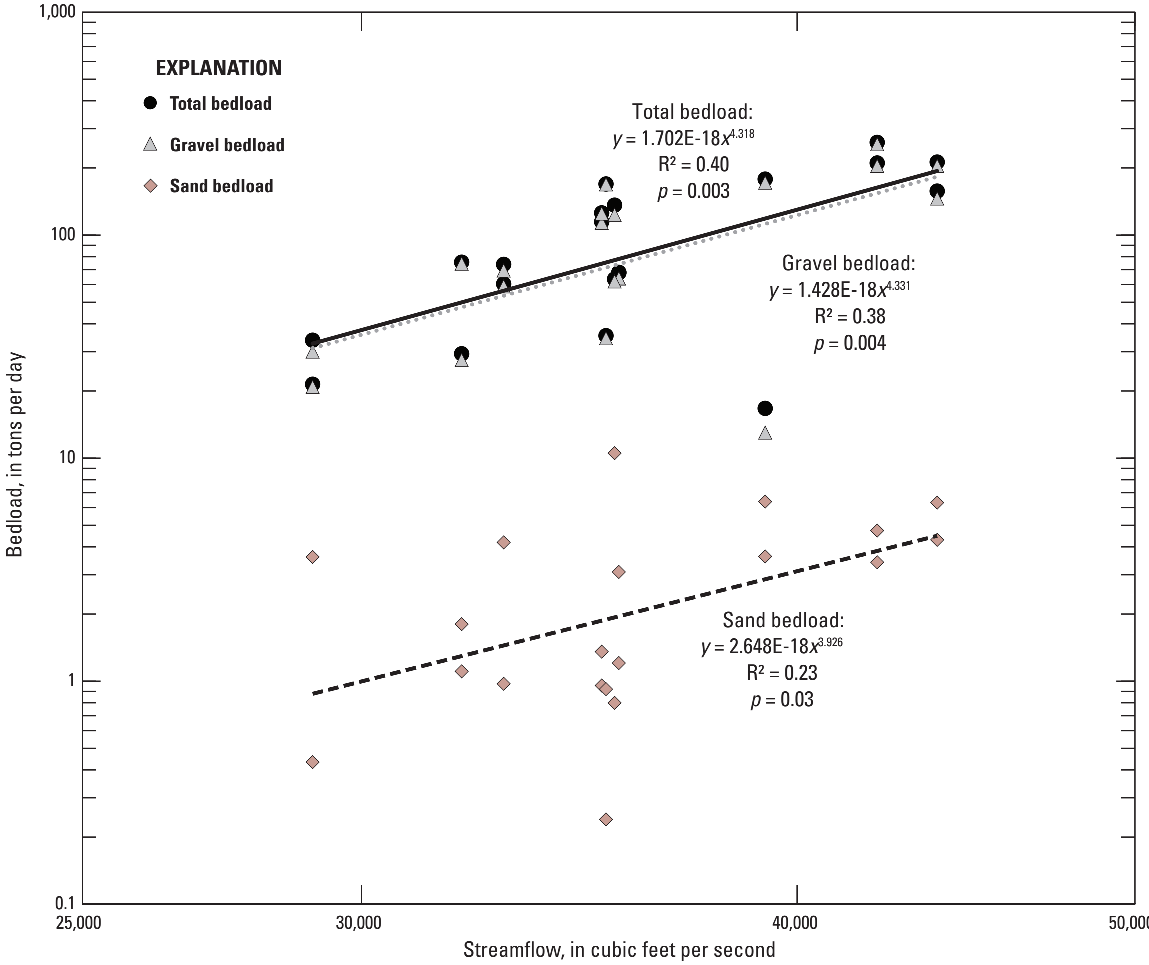


Figure 8. Relations between streamflow and total, gravel, and sand bedload transport at the Crossport site (USGS 12308500) in the Kootenai River, Idaho, water years 2011–13.

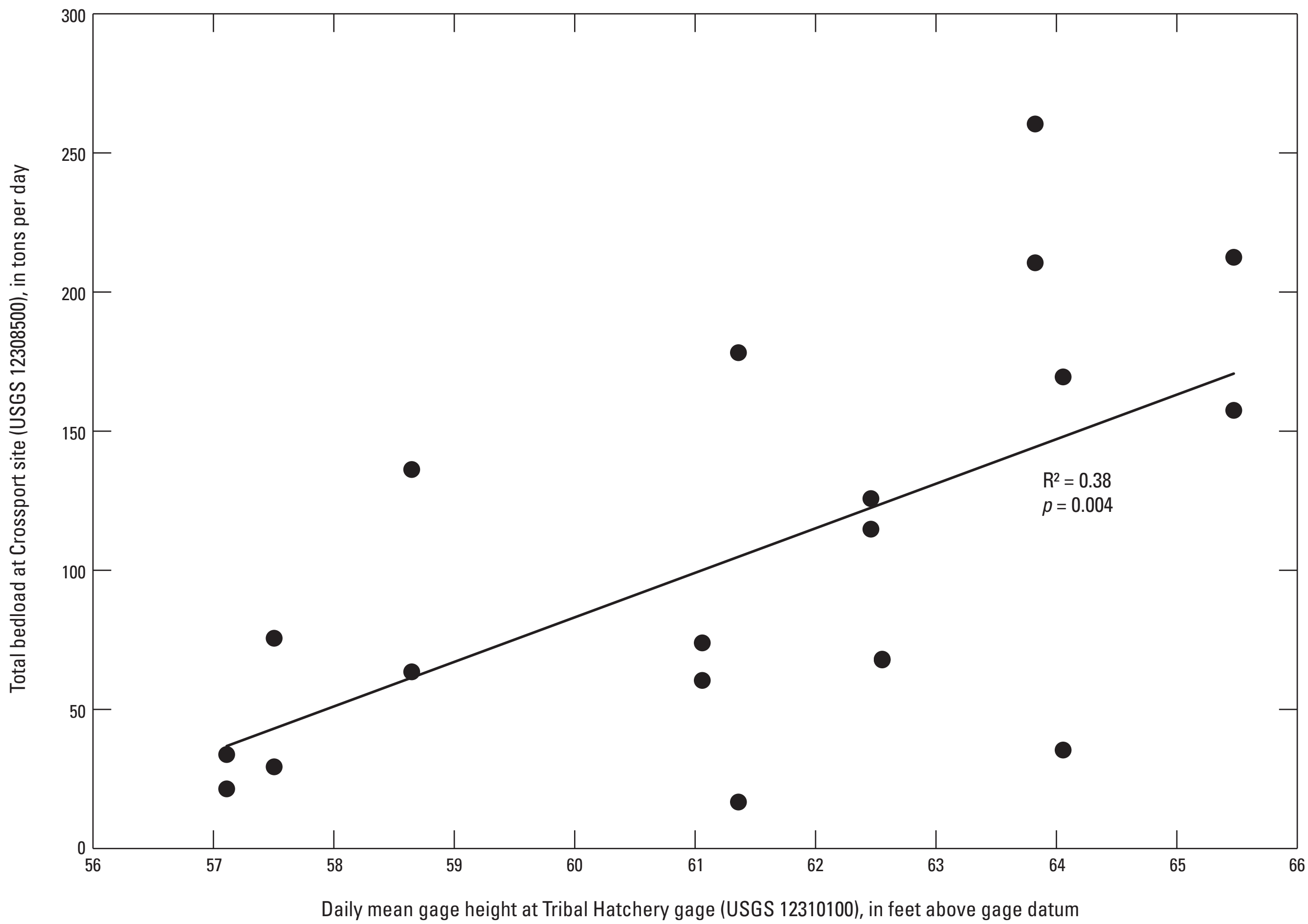


Figure 9. Relation between daily mean gage height in the Kootenai River at the Tribal Hatchery site (USGS 12310100) and total bedload from samples collected at the Crossport site (USGS 12308500), Idaho, water years 2011–13. Gage heights for this site are referenced to the gage datum, which is 1,699.88 feet above North American Vertical Datum of 1988.

Similar to suspended sediment, results from bedload sediment sampling at the Crossport site were compared to regression and envelope lines developed by Holnbeck (2005) from results of samples collected during comparative conditions in nine other coarse-bedded rivers with minimal regulation in the Western United States. Holnbeck (2005) also plotted bedload results from other rivers, including the Yellowstone River, in comparison with the regression and envelope lines. For comparison with the Holnbeck (2005) lines, the bedload transport curve developed for the Crossport site, relating streamflow and bedload, was used to estimate bedload at the 30,000 ft^3/s bankfull streamflow defined in Kootenai Tribe of Idaho (2009). In the case of bedload, the second condition to define "bankfull" streamflow, a downstream water level of 1,754 ft at the Kootenai River at Porthill (USGS 12322000), was disregarded because the backwater zone does not typically extend to the Crossport site until streamflow exceeds 50,000 ft^3/s. The estimated bedload transport rate at the Crossport site in relation to unregulated drainage area (drainage area downstream of Libby Dam, 3,950 mi^2; fig. 10) was substantially lower than estimated by the bedload regression and envelope lines developed by Holnbeck (2005) and was similar to bedload at sites with drainage areas in the range 70–100 mi^2. Holnbeck (2005) noted that rivers with extensive braiding typically have highly unstable and mobile streambed conditions, and their bedload can plot above the regression and envelope lines. In contrast, although the Crossport site is in the "braided" reach of the Kootenai River, limited variability of streamflow through regulation and limited sediment supply mitigate river channel changes and the mobility of bedload sediment.

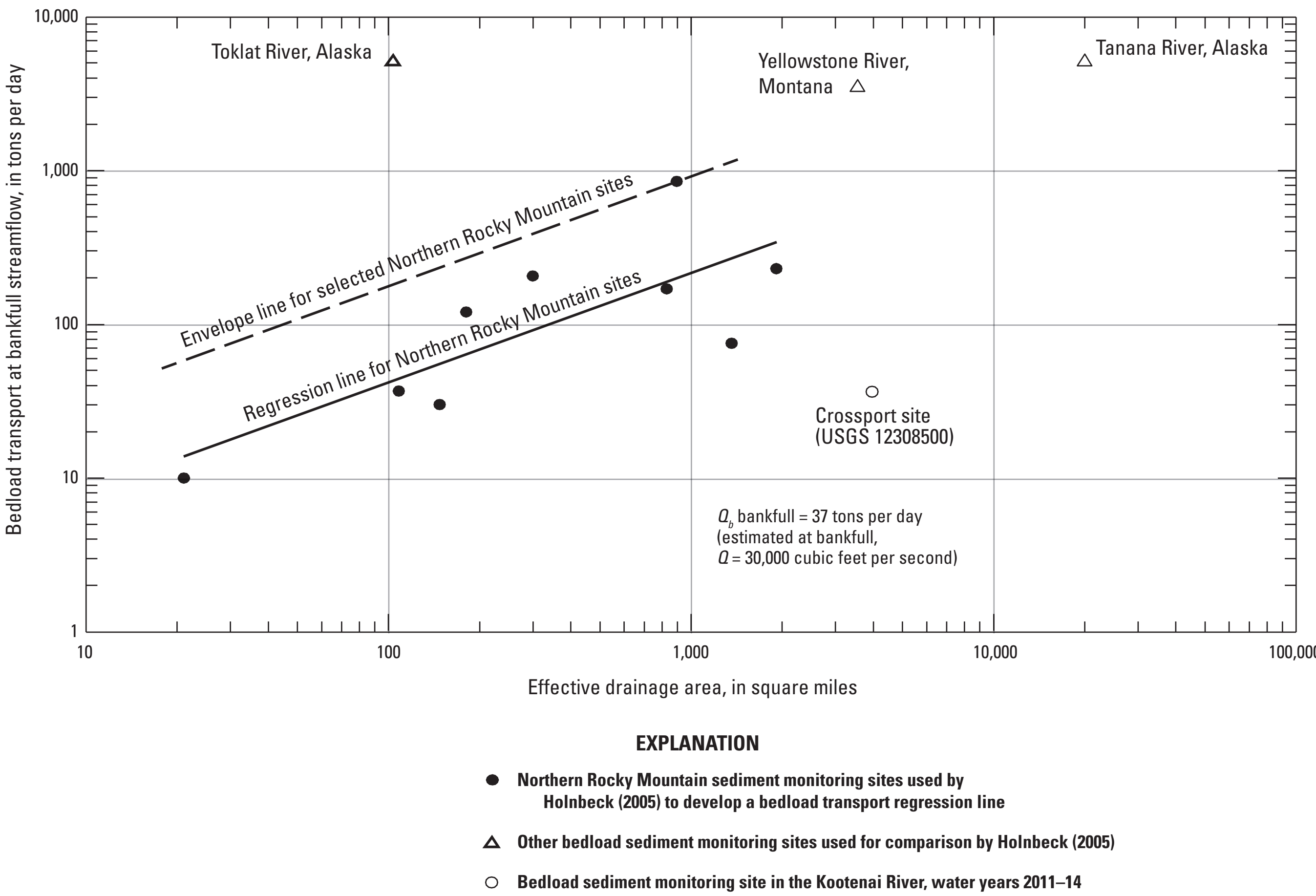


Figure 10. Bedload transport at bankfull streamflow for selected sites in the Western United States and the Crossport site (USGS 12308500), Kootenai River, Idaho, water years 2011–13. Base data and modified figure from Holnbeck, 2005. Drainage area shown for the Kootenai River is the part considered relatively "unregulated," downstream of Libby Dam.

Evaluation of Sediment Surrogate Ratings

Sediment surrogate ratings were developed to compute time series estimates of SSC and SSL, which were used by KTOI and RDG to calibrate and validate sediment transport models and by USGS Geomorphology and Sediment Transport Laboratory to support morphodynamic modeling in the study area. Results of the acoustic surrogate (backscatter based) and R-LOADEST (streamflow based) ratings are discussed and compared to assess which method provided the most direct surrogate measure of SSC and SSL at the study sites.

Sediment Acoustic Surrogate Ratings

Final selected sediment acoustic surrogate ratings are summarized in table 4. Two samples (collected on April 27, 2012, and April 6, 2013) were removed from the rating analysis for SSC and fines concentrations at all three Kootenai River sites because values for the LDR term were extremely high (about 5, meaning that streamflow at the site was five times as high as streamflow at the streamgage below Libby Dam, USGS 12301933). The high LDR values caused the samples to be outliers in the regression model. These samples were collected during rain-on-snow events during which streamflow and sediment concentrations rapidly varied. Application of a lag time in the calculation of LDR did not substantially improve the acoustic surrogate ratings, so in the end, the two samples were removed from the rating analysis for SSC and fines concentrations. The samples were used in the rating analysis for sand concentrations because the LDR term was not statistically significant and so was not included in those ratings.

As mentioned in section, “Sediment Transport Patterns,” the box coefficient ratings between the autosampler grab and EWI samples collected at the Crossport site were poor, and the rating for sand concentrations was not statistically significant. The autosampler intake at the Crossport site might be in a depositional or eddy zone at certain streamflows, which would likely result in a poor proportional rating between sediment concentrations at the intake and overall EWI sample concentrations. In the end, the box coefficient ratings, and resulting estimates of EWI concentrations on the basis of autosample concentrations, did not substantially improve the acoustic surrogate ratings at the Crossport site. Additionally, including the EWI concentrations estimated using the box coefficient rating resulted in SSC and SSL estimates that were inconsistent relative to the Below Moyie and Tribal Hatchery sites. As a result, the acoustic surrogate ratings for the Crossport site were developed using only the directly measured EWI sample concentrations. Use of the box coefficient ratings and resulting estimates of EWI concentrations substantially improved the range and fit of the acoustic surrogate ratings and were used in a weighted least squares analysis to develop all acoustic surrogate ratings at the Below Moyie site. For example, inclusion of the box coefficient rating-generated EWI estimates improved the rating R^2 by 5 percent for sands and 6 percent for total SSC and reduced residual standard error by 67 percent for sands and 49 percent for total SSC at the upper end of the rating (1.5MHz ABS_{corr} > 75 dB or 3MHz ABS_{corr} > 67dB).

At the Below Moyie and Crossport sites, where two ADVMs of different frequencies were installed, total suspended-sediment and fines concentrations were best fitted with ratings developed using the high frequency ADVM (3-MHz), which was expected on the basis of past research and acoustic theory. Sand concentrations were best fitted with ratings developed using the low frequency ADVM (1.5-MHz). Ratings for total suspended-sediment, fines, and sands concentrations were successfully fitted to a single frequency 1.5-MHz ADVM at the Tribal Hatchery site, although estimates probably would have been improved if a second frequency ADVM had been used. Plots of ABS_{corr} against total suspended-sediment, sand, and fines concentrations at the Below Moyie and Crossport sites all showed breakpoints or changes in rating slope at a specific ABS_{corr}, which varied on the basis of site and sediment type (fig. 11, table 4). As a result, different ratings were prescribed to estimate sediment concentrations whether corrected acoustic backscatter was above or below the rating breakpoint. The breakpoints probably represented a change in sediment source (a particular tributary or group of tributaries) or change in particle-size distribution that resulted in a change in response for a single frequency ADVM. Various breakpoints were evaluated in each rating in an attempt to achieve a smooth transition between ratings and an optimum fit for the high concentrations. The LDR term also was statistically significant and substantially improved the fit for the total and fines concentration ratings but was not significant for the sand concentrations. Graphs of measured (on the basis of samples) and estimated (on the basis of final selected acoustic surrogate ratings shown in table 4) SSC and sand concentrations (fig. 12) show that estimated concentrations were reasonably close to and followed the trend of measured concentrations, as evidenced by the plotted points position relative to the 1:1 lines. Some scatter was noted, particularly at high concentrations of SSC and sand, but might have been because of limited samples collected at high concentrations. The uncertainty introduced by the inclusion of the box coefficient rating-generated EWI sample concentrations in the ratings developed at the Below Moyie site (table 3) was thought to be reduced by weighting samples and performing a weighted least squares analysis; however, little precedent for similar research exists to know whether the rating uncertainty is fully represented by the prediction intervals. Concentrations in samples collected in 2014 to verify the ratings, although low relative to the range of concentrations measured in 2011–13, generally verified and were in the scatter and 95-percent prediction intervals of the acoustic surrogate ratings (fig. 12).

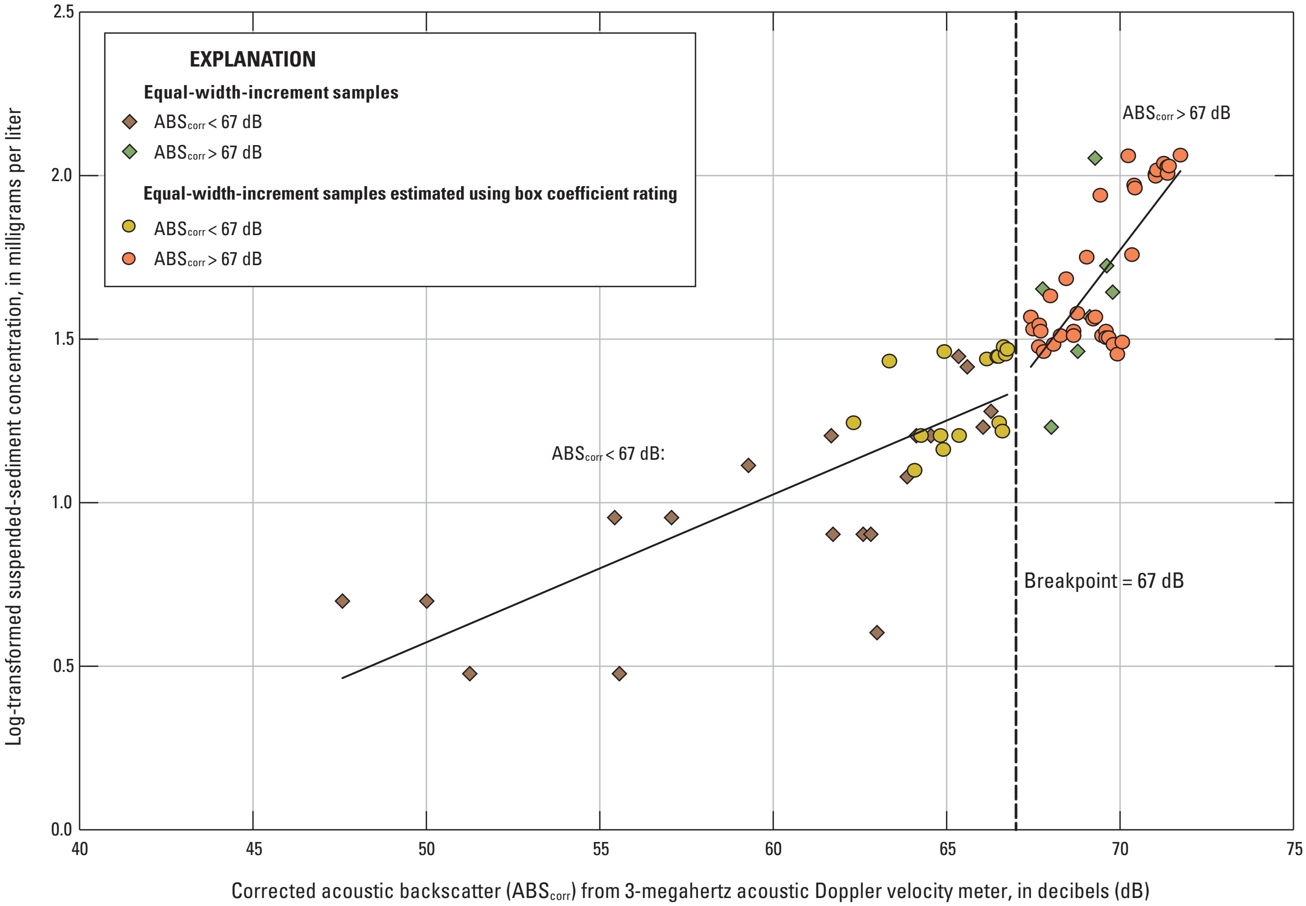


Figure 11. Relation between corrected 3-megahertz acoustic backscatter and log-transformed suspended sediment with breakpoint in slope at a corrected acoustic backscatter of 67 decibels Below Moyie site (USGS 12308000), Kootenai River, Idaho, water years 2011–13.

Table 4. Sediment acoustic surrogate ratings and regression statistics for sediment monitoring sites in the Kootenai River, Idaho, water years 2011–13.

[**Abbreviations:** R^2, coefficient of determination; R^2_a, coefficient of determination adjusted for multiple explanatory variables; mg/L, milligrams per liter; BCF, Duan's bias correction factor; USGS, U.S. Geological Survey; MHz, megaHertz; dB, decibel; SSC, total suspended-sediment concentration (mg/L); ABS_{corr}, acoustic backscatter corrected for beam spreading and attenuation by water and sediment (dB); log, logarithm; LDR, Libby Dam Ratio; <, less than; >, greater than; NA, not applicable]

Sediment type	Breakpoint	Number of samples used for rating	Rating	R^2 or R^2_a	Residual standard error (mg/L)	BCF
			Below Moyie site (USGS 12308000)			
Total suspended-sediment concentration	3MHz_ABS_{corr} < 67 dB	[1]34	$SSC = 10^{[(0.0328\times 3MHz\_ABScorr+1.052\times\log(LDR)-1.163)]}\times 1.040$	0.79	1.4	1.040
	3MHz_ABS_{corr} > 67 dB	[1]42	$SSC = 10^{[(0.0475\times 3MHz\_ABScorr+1.305\times\log(LDR)-2.099)]}\times 1.022$	0.84	1.3	1.022
Sand concentration	1.5MHz_ABS_{corr} < 75 dB	26	$Sand = 10^{[(0.0436\times 1.5MHz\_ABScorr-2.575)]}\times 1.179$	0.45	2.1	1.179
	1.5MHz_ABS_{corr} > 75 dB	52	$Sand = 10^{[(0.0801\times 1.5MHz\_ABScorr-5.236)]}\times 1.004$	0.64	1.2	1.004
Fines concentration	3MHz_ABS_{corr} < 67 dB	[1]34	$Fines = 10^{[(0.0313\times 3MHz\_ABScorr+1.286\times\log(LDR)-1.275)]}\times 1.036$	0.84	1.4	1.036
	3MHz_ABS_{corr} > 67 dB	[1]42	$Fines = 10^{[(0.0373\times 3MHz\_ABScorr+1.914\times\log(LDR)-1.743)]}\times 1.027$	0.88	1.3	1.027
			Crossport site (USGS 12308500)[2]			
Total suspended-sediment concentration	3MHz_ABS_{corr} < 67.5 dB	[1]19	$SSC = 10^{[(0.0480\times 3MHz\_ABScorr+0.4397\times\log(LDR)-2.011)]}\times 1.032$	0.85	1.4	1.032
	3MHz_ABS_{corr} > 67.5 dB	[1]7	$SSC = 10^{[(0.0319\times 3MHz\_ABScorr+1.381\times\log(LDR)-1.042)]}\times 1.038$	0.64	1.5	1.038
Sand concentration	1.5MHz_ABS_{corr} < 78.7 dB	19	$Sand = 10^{[(0.0650\times 1.5MHz\_ABScorr-4.228)]}\times 1.095$	0.77	1.7	1.095
	1.5MHz_ABS_{corr} > 78.7 dB	9	$Sand = 10^{[(0.2038\times 1.5MHz\_ABScorr-15.24)]}\times 1.005$	0.93	1.1	1.005
Fines concentration	3MHz_ABS_{corr} < 67.1 dB	[1]16	$Fines = 10^{[(0.0394\times 3MHz\_ABScorr+0.7045\times\log(LDR)-1.706)]}\times 1.040$	0.77	1.4	1.040
	3MHz_ABS_{corr} > 67.1 dB	[1]10	$Fines = 10^{[(0.0755\times 3MHz\_ABScorr+1.262\times\log(LDR)-4.151)]}\times 1.047$	0.67	1.5	1.047
			Tribal Hatchery site (USGS 12310100)[3]			
Total suspended-sediment concentration	NA	[4]25	$SSC = 10^{[(0.0496\times 1.5MHz\_ABScorr+0.7165\times\log(LDR)-2.471)]}\times 1.089$	0.75	1.7	1.089
Sand concentration	NA	27	$Sand = 10^{[(0.0740\times 1.5MHz\_ABScorr-4.679)]}\times 1.125$	0.78	1.9	1.125
Fines concentration	NA	[4]25	$Fines = 10^{[(0.0400\times 1.5MHz\_ABScorr+1.078\times\log(LDR)-2.009)]}\times 1.098$	0.72	1.7	1.098

[1]One sample removed as an outlier for LDR.

[2]EWI samples only used for model development though EWI-derived concentrations based on autosamples were available.

[3]One sample result was erroneous due to suspicion of sampler hitting sand dune during sample collection and was not used in analysis.

[4]Two samples removed as outliers for LDR (same total number of samples removed from analysis for other sites).

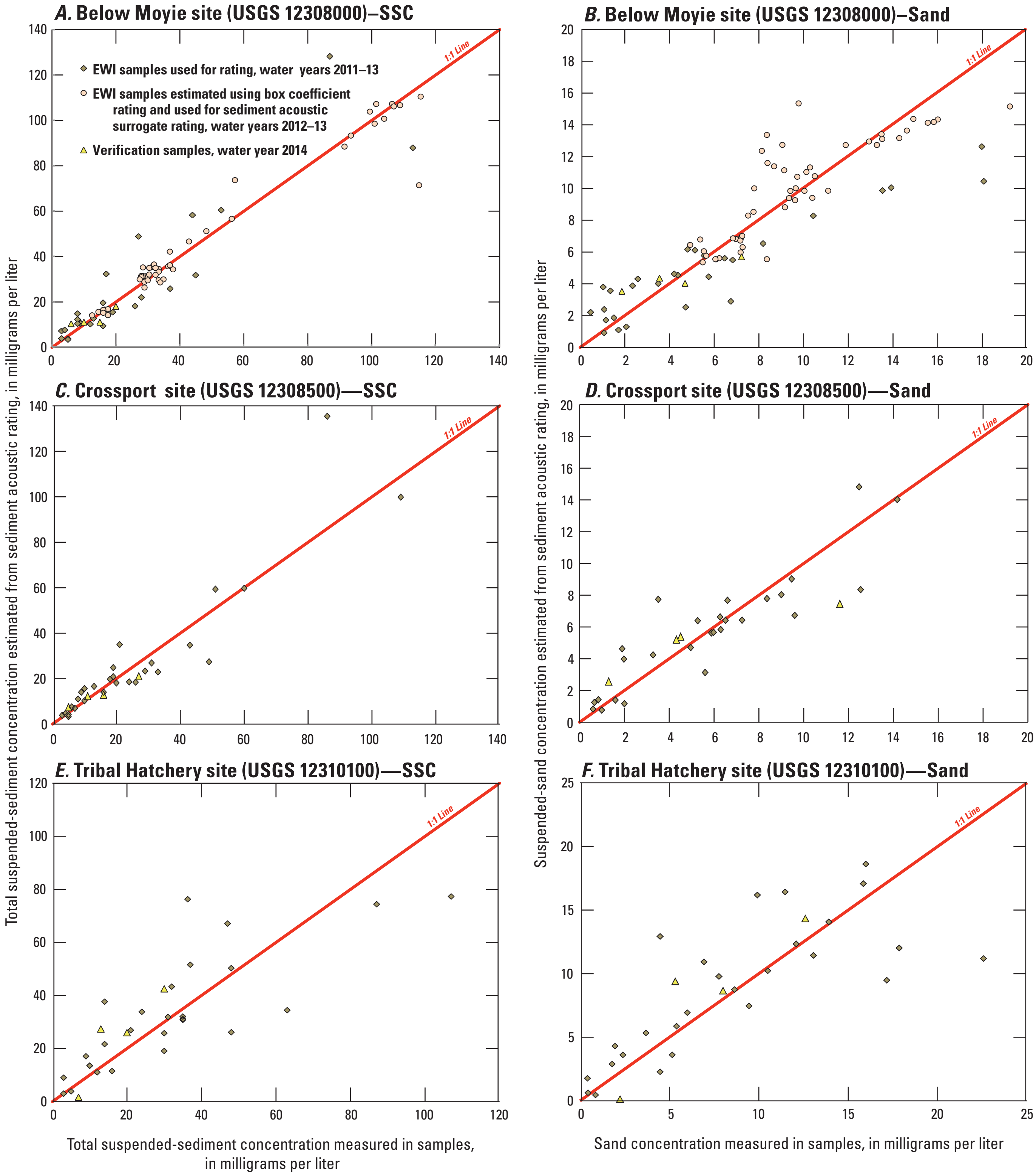


Figure 12. Measured and estimated total suspended-sediment and sand concentrations on the basis of surrogate ratings with acoustic backscatter for samples collected at sediment monitoring sites in the Kootenai River, Idaho, water years 2011–14. (SSC, suspended-sediment concentration)

Regression statistics and graphical fit of the sediment acoustic surrogate ratings were compared with simple ratings developed using ordinary least squares regression between streamflow and suspended-sediment concentrations (table 5) to verify that the sediment acoustic surrogate ratings provided an improved and more direct fit of sampled data. The regression statistics of the simple ratings with streamflow were compared to the sediment acoustic ratings using all data at the Tribal Hatchery site and using only data at high ABS_{corr}, above the breakpoint used to fit separate sediment acoustic surrogate ratings to high suspended-sediment concentrations at the Below Moyie and Crossport sites. In nearly all cases, the sediment acoustic surrogate ratings produced higher (10–62 percent) R^2, lower (15–48 percent) standard error, and better visual fit of sampled suspended-sediment concentrations than streamflow alone, further supporting the hypothesis that streamflow alone is a poor estimator of sediment transport in the Kootenai River. The R^2 for the sand model at the Below Moyie site did not improve when switching from streamflow alone to acoustics, but the model residual standard error was reduced by 28 percent, indicating an overall better fit by the sediment acoustic surrogate rating.

Variability and uncertainty in the individual ratings were caused by many physical factors of sediment transport including the magnitude of the suspended component, mobility of bed material and armoring, non-equilibrium (supply limited) transport of sediment, relative magnitudes of the tributary inflows, timing of releases of stored water for water management, and proximity of episodic sediment sources. Additional uncertainty might have been contributed by the presence of organic matter which was detected by the ADVMs but was not represented in the SSC analytical results, although organic matter concentrations were low (0–8 mg/L). Acoustic surrogate ratings for sand had higher uncertainty and greater scatter than acoustic surrogate ratings for total SSC and fines, probably for two reasons: (1) sand concentrations were very low (all EWI sample results had less than or equal to 23 mg/L sand), and (2) the ADVMs measured backscatter about mid-depth in the water column where sand concentrations might not have changed proportionally with the overall EWI sand concentration. Efforts to develop acoustic surrogate ratings for the Snake River, described in Wood and Teasdale (2013) and Clark and others (2013), showed that the ADVMs probably measured a zone of water higher in the water column than where the highest concentrations of sand were transported. As a result, the backscatter response did not change substantially during periods of changing sand concentration, resulting in higher rating uncertainty and an overall underestimation of sand concentrations using the acoustic surrogate rating. A similar phenomenon might be occurring at the Kootenai River study sites, although overall, average sand concentrations measured in EWI samples were 83 percent lower in the Kootenai River than what was measured in the Snake River study. Additionally, the ADVM backscatter measurements were not optimized for sediment estimation and have less than ideal resolution and sensitivity to changing concentrations, particularly at low concentrations less than about 20 mg/L. As a result, some of the uncertainty of the acoustic surrogate ratings, particularly for sands, might also have been because of ADVM operational limits.

A theoretical Rouse-Vanoni profile (Vanoni, 1975) was developed to estimate a vertical sand concentration profile and validate a point on the acoustic surrogate rating for sand for the Below Moyie site. The profile was calculated for a sample collected on June 5, 2012, which had the highest sand concentration of any EWI sample collected at the Below Moyie site. The profile was developed on the basis of a sediment particle fall velocity relation (described in Dietrich [1982]), shear velocity, bed shear stress, and sand concentration data from an autosampler grab sample collected at the time of the EWI (representing concentration data at a known point above the streambed). Sand concentrations in the autosampler grab and EWI samples were 40 and 18 mg/L, respectively, on June 5, 2012. The theoretical Rouse-Vanoni profile for this sample event showed sand concentrations would have been roughly 15 mg/L around the depth of the ADVM (fig. 13). The acoustic surrogate rating on the basis of ADVM backscatter estimated an EWI concentration of 12.5 mg/L, 30 percent lower than the sampled EWI concentration. The estimate is reasonable, however, on the basis of the ADVM's location in the water column and the estimated Rouse-Vanoni profile, which shows a substantial increase in sand concentrations with depth because of particle density and other factors. Sand concentrations at mid-depth in the water column probably do not change as proportionally with EWI sand concentrations as would sand concentrations lower in the water column. As a result, more uncertainty is expected in the acoustic surrogate ratings for sand than for total SSC and fines concentrations, which are typically better mixed and more equally distributed in the water column than sand concentrations.

Table 5. Linear regressions between streamflow and suspended-sediment concentrations and comparison in regression statistics with sediment acoustic surrogate ratings for sediment monitoring sites in the Kootenai River, Idaho, water years 2011–13.

[Bias correction factor not shown for simple ratings between streamflow and suspended-sediment concentrations because ratings were not used to calculate continuous estimates of suspended-sediment concentrations and loads. Simple ratings with streamflow were compared to the sediment acoustic ratings using all data at the Tribal Hatchery site and using only data at high ABS_{corr}, above the breakpoint used to fit separate sediment acoustic surrogate ratings to high suspended-sediment concentrations at the Below Moyie and Crossport sites (see table 4; for example, at the Below Moyie site, 1.5MHz $ABS_{corr} > 75$db and 3.0MHz $ABS_{corr} > 67$ dB). **Abbreviations:** R^2, coefficient of determination; mg/L, milligrams per liter; ABS_{corr}, acoustic backscatter corrected for beam spreading and attenuation by water and sediment (dB); USGS, U.S. Geological Survey; SSC, total suspended-sediment concentration (mg/L); log, logarithm; Q, streamflow (ft^3/s)]

Sediment type	Number of samples used for rating	Simple rating between streamflow and suspended-sediment concentrations	R^2	Residual standard error (mg/L)	Difference in R^2 from sediment acoustic rating (percent)	Difference in residual standard error from sediment acoustic rating (percent)
Below Moyie site (USGS 12308000)						
Total suspended-sediment concentration	78	$SSC = 10^{(1.408 \times \log(Q) - 4.962)}$	0.57	1.8	-38	32
Sand concentration	78	$Sand = 10^{(1.363 \times \log(Q) - 5.383)}$	0.64	1.6	0 (no difference)	28
Fines concentration	78	$Fines = 10^{(1.438 \times \log(Q) - 5.238)}$	0.48	2.0	-59	42
Crossport site (USGS 12308500)						
Total suspended-sediment concentration	28	$SSC = 10^{(1.111 \times \log(Q) - 3.667)}$	0.58	1.9	-10	24
Sand concentration	28	$Sand = 10^{(1.204 \times \log(Q) - 4.678)}$	0.66	1.8	-34	48
Fines concentration	28	$Fines = 10^{(1.097 \times \log(Q) - 3.757)}$	0.50	2.0	-29	28
Tribal Hatchery site (USGS 12310100)						
Total suspended-sediment concentration	[1]27	$SSC = 10^{(0.946 \times \log(Q) - 2.829)}$	0.44	2.0	-52	16
Sand concentration	[1]27	$Sand = 10^{(1.182 \times \log(Q) - 4.461)}$	0.50	2.2	-43	15
Fines concentration	[1]27	$Fines = 10^{(0.867 \times \log(Q) - 2.635)}$	0.38	2.1	-62	21

[1]One sample result was erroneous due to suspicion of sampler hitting sand dune during sample collection and was not used in analysis.

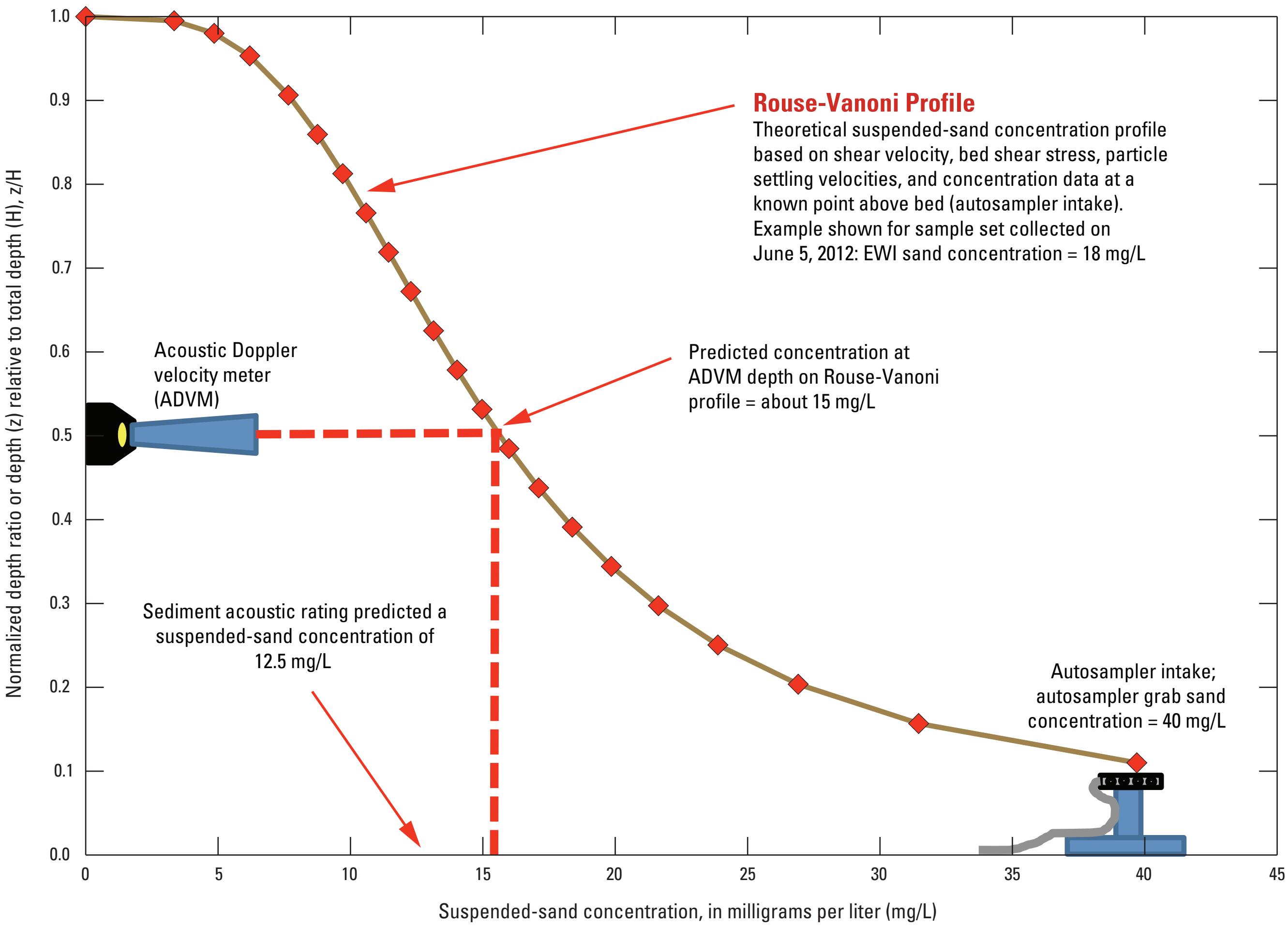


Figure 13. Theoretical suspended-sand concentration profile with normalized depth compared with suspended-sand concentration from an equal-width-increment (EWI) sample collected on June 5, 2012, and estimated using a 1.5-MHz acoustic Doppler velocity meter at the Below Moyie site (USGS 12308000), Kootenai River, Idaho.

Sediment Streamflow Surrogate Ratings

The sediment streamflow surrogate ratings developed using R-LOADEST fit measured SSL reasonably well (R^2 or R^2_a 0.87–0.95; table 6). As with the acoustic surrogate ratings, separate streamflow surrogate ratings were fit to the total suspended, sand, and fines loads. Quadratic flow, seasonality, and LDR were selected as explanatory variables in most of the best-fit ratings, depending on sediment type. When calculating LDR for the streamflow surrogate ratings, the application of a lag time to streamflow values used in the calculation improved fit for the Below Moyie and Crossport sites. UV (15-minute) streamflow from the streamgage below Libby Dam (USGS 12301933) was lagged in time by adding 11 hours to each UV streamflow at the Crossport site and 10 hours to each UV streamflow at the Below Moyie site, prior to calculation of LDR using equation 4. For the Tribal Hatchery site streamflow surrogate rating, best fit was determined by calculating LDR using daily mean streamflow values without lag. The explanatory variable tested to represent changing SSC and SSL on the rising and falling limbs of the hydrograph (hysteresis effects), dQ_k, was not statistically significant and did not substantially contribute to the rating fit for any site. In most cases, inclusion of the quadratic flow, seasonality, and LDR variables helped to represent hysteresis effects. The sand rating for the Crossport site was the only rating that did not include explanatory variables other than streamflow, and overall fit was poorer than ratings for other sediment types and sites (table 6). Additionally, the seasonality terms were statistically significant for the Crossport site, similar to other sites, but were not selected for the final rating because of patterns in the residuals and other regression diagnostics.

Comparison of Results

R-LOADEST produces regression models for SSL (table 6) and not for SSC, so the regression statistics for the sediment streamflow surrogate ratings could not be directly compared with those from the acoustic surrogate ratings. The streamflow surrogate ratings based on R-LOADEST were developed independently of the acoustic surrogate ratings to ensure the ratings were truly the best fit of the available data. As a result, some explanatory variables were applied in slightly different ways between the streamflow and acoustic surrogate ratings, most notably, the use of different time steps in calculation of the LDR term. Additionally, the summation of loads for suspended fines and sands did not exactly equal the loads for total suspended sediment for both the sediment acoustic and sediment streamflow surrogate ratings because regression models were fit and optimized separately for each sediment classification.

The streamflow surrogate ratings produced average annual SSL estimates that were 8–32 percent higher, depending on site and sediment type, than estimates produced using the acoustic surrogate ratings (table 7). The greatest differences between the streamflow and acoustic surrogate ratings were observed for the sand ratings (streamflow rating estimates 16–32 percent higher) and particularly for the ratings at Crossport compared to the other sites (streamflow surrogate rating estimates 23–32 percent higher). The streamflow surrogate ratings at the Crossport site produced annual SSL estimates that did not align well with estimates from other streamflow surrogate ratings at the upstream Below Moyie site and downstream Tribal Hatchery site. The estimates indicated an increase in SSL that did not make sense because of the lack of a defined, large sediment source between sites.

The streamflow surrogate rating produced monthly estimates for total suspended-sediment and suspended-sand loads that were comparable or slightly higher than estimates produced using the acoustic surrogate ratings for most months (table 7; fig. 14). Some higher percent differences between SSL estimated using the two surrogate methods (as much as 135 percent difference in monthly SSL at the Tribal Hatchery site) were observed in the winter, January–February. One sample set was collected at all sites in the January–February time frame on February 22, 2012. The results of that sample set matched the estimates from the acoustic surrogate rating more closely than the estimates from the streamflow surrogate rating. Sediment concentrations were expected to be relatively low in January and February on the basis of visual observations of water clarity and results of the one sample set collected on February 22, 2012. The higher estimates produced by the streamflow surrogate rating seemed to be false and were perhaps the result of including the seasonality term because the percentage of difference was most pronounced for sites with ratings that included that term. Additional samples are needed to verify that the sediment acoustic surrogate ratings produce more accurate estimates of SSL during winter.

Suspended-sediment concentrations were back-calculated from SSL generated using the streamflow surrogate ratings to compare results with the acoustic surrogate method for a storm event in May 2013 at the Below Moyie site during which several samples were collected (fig. 15). Sand concentrations during the event peaked near the first increase in streamflow, according to the acoustic surrogate rating. Sand concentrations in samples collected on and immediately after this first increase matched the estimates from the acoustic surrogate rating, except for the concentration in the sample collected later in the event, on May 13 at 12:11 p.m., which matched the estimates from the streamflow surrogate rating.

Table 6. Sediment streamflow surrogate load ratings and regression statistics for sediment monitoring sites in the Kootenai River, Idaho, water years 2011–13.

[**Abbreviations:** USGS, U.S. Geological Survey; R^2, coefficient of determination; R^2_a, coefficient of determination adjusted for multiple explanatory variables; mg/L, milligrams per liter; BCF, Bradu-Mundlak bias correction factor; SSL, suspended-sediment load (tons/day); EXP, exponent; *Q*, streamflow (ft^3/s); T, centered decimal time from the beginning of the calibration (study) period (yrs); sin, sine; cos, cosine; ln, natural logarithm; LDR, Libby Dam Ratio]

Sediment type	Number of samples used for rating	Rating	R^2 or R^2_a	Residual standard error (tons/day)	BCF
		Below Moyie site (USGS 12308000)			
Total suspended-sediment load	28	$SSL = EXP^{[(1.896\times\ln(Q)+0.7319\times\ln(Q^2)+0.2423\times\sin(2\pi T)+0.3399\times\cos(2\pi T)+1.027\times\ln(LDR)+12.14)]}\times1.051$	0.95	1.4	1.051
Sand load	28	$Sand = EXP^{[(2.213\times\ln(Q)+1.226\times\ln(Q^2)+0.2324\times\sin(2\pi T)+0.4348\times\cos(2\pi T)+10.92)]}\times1.091$	0.91	1.6	1.091
Fines load	28	$Fines = EXP^{[(1.804\times\ln(Q)+0.5389\times\ln(Q^2)+0.2942\times\sin(2\pi T)+0.3111\times\cos(2\pi T)+1.304\times\ln(LDR)+11.75)]}\times1.065$	0.94	1.5	1.065
		Crossport site (USGS 12308500)			
Total suspended-sediment load	28	$SSL = EXP^{[(1.812\times\ln(Q)+0.3883\times\ln(Q^2)+1.197\times\ln(LDR)+12.37)]}\times1.068$	0.94	1.5	1.068
Sand load	28	$Sand = EXP^{[(2.180\times\ln(Q)-9.639)]}\times1.158$	0.87	1.8	1.158
Fines load	28	$Fines = EXP^{[(1.725\times\ln(Q)+0.379\times\ln(Q^2)+1.507\times\ln(LDR)+11.88)]}\times1.075$	0.94	1.5	1.075
		Tribal Hatchery site (USGS 12310100)			
Total suspended-sediment load	[1]27	$SSL = EXP^{[(1.876\times\ln(Q)+0.4802\times\ln(Q^2)+0.6030\times\sin(2\pi T)+0.6090\times\cos(2\pi T)+0.5927\times\ln(LDR)+12.78)]}\times1.067$	0.94	1.5	1.067
Sand load	[1]27	$Sand = EXP^{[(2.188\times\ln(Q)+0.4109\times\ln(Q^2)+0.8989\times\sin(2\pi T)+0.6786\times\cos(2\pi T)+11.57)]}\times1.112$	0.92	1.6	1.112
Fines load	[1]27	$Fines = EXP^{[(1.758\times\ln(Q)+0.5011\times\ln(Q^2)+0.4525\times\sin(2\pi T)+0.5999\times\cos(2\pi T)+0.9493\times\ln(LDR)+12.33)]}\times1.071$	0.93	1.5	1.071

[1]One sample result was erroneous due to suspicion of sampler hitting sand dune during sample collection and was not used in analysis.

Table 7. Monthly, annual, and average annual total suspended-sediment, sand, and fines loads estimated using acoustic surrogate and streamflow surrogate ratings for sediment monitoring sites in the Kootenai River, Idaho, water years 2011–14.

[Loads are presented in tons/month or tons/year, depending on whether the time period is a month or year. **Abbreviations:** USGS, U.S. Geological Survey; WY, water year]

Time period	Below Moyie site (USGS 12308000)					
	Total Suspended		Sands		Fines	
	Acoustic surrogate rating	Streamflow surrogate rating	Acoustic surrogate rating	Streamflow surrogate rating	Acoustic surrogate rating	Streamflow surrogate rating
October	1,700	2,200	400	700	1,100	1,300
November	8,400	8,600	3,000	2,800	5,500	5,600
December	11,200	14,800	3,800	5,000	7,300	9,600
January	4,000	5,700	700	1,500	3,200	4,100
February	3,800	5,400	1,100	1,700	2,500	3,700
March	10,400	10,200	2,500	2,200	7,400	8,200
April	37,300	37,800	8,000	8,600	30,500	30,100
May	61,000	65,300	14,000	15,900	44,700	48,700
June	47,300	54,900	15,400	18,800	32,300	36,300
July	18,600	22,900	8,100	11,200	11,600	13,500
August	5,000	3,700	1,900	1,000	3,300	2,600
September	2,200	2,000	700	600	1,500	1,300
WY2011	277,700	254,600	62,400	64,300	201,000	185,800
WY2012	286,400	333,900	86,100	118,200	207,700	225,700
WY2013	148,100	168,400	45,500	47,000	104,300	122,200
WY2014	130,800	176,900	44,500	50,400	91,200	126,300
Total water years 2011–14	843,000	933,800	238,500	279,900	604,200	660,000
Average annual	210,800	233,500	59,600	70,000	151,100	165,000

Time period	Crossport site (USGS 12308500)					
	Total Suspended		Sands		Fines	
	Acoustic surrogate rating	Streamflow surrogate rating	Acoustic surrogate rating	Streamflow surrogate rating	Acoustic surrogate rating	Streamflow surrogate rating
October	1,300	2,400	200	400	1,100	1,700
November	11,500	9,700	4,200	4,800	7,300	6,200
December	14,500	14,000	4,800	7,300	9,400	8,900
January	3,300	4,500	600	1,100	2,600	3,400
February	4,500	3,900	1,200	1,300	3,100	2,700
March	9,800	9,500	2,900	2,900	7,100	7,100
April	37,600	39,400	10,500	11,300	27,100	29,700
May	57,400	76,900	18,500	21,500	41,200	55,000
June	46,600	69,600	16,700	24,000	31,200	46,300
July	23,500	31,000	8,700	14,700	15,000	18,900
August	7,100	7,200	2,000	3,500	4,800	4,700
September	2,300	3,100	500	1,000	1,700	2,100
WY2011	276,700	304,500	75,300	92,800	193,900	215,200
WY2012	309,500	379,700	100,000	132,200	212,600	256,900
WY2013	157,900	199,700	57,000	76,200	107,700	137,800
WY2014	133,900	201,400	50,800	74,100	92,400	136,600
Total water years 2011–14	878,000	1,085,300	283,100	375,300	606,600	746,500
Average annual	219,500	271,300	70,800	93,800	151,700	186,600

Table 7. Monthly, annual, and average annual total suspended-sediment, sand, and fines loads estimated using acoustic surrogate and streamflow surrogate ratings for the sediment monitoring sites in the Kootenai River, Idaho, water years 2011–14.—Continued

[Loads are presented in tons/month or tons/year, depending on whether the time period is a month or year. **Abbreviations:** USGS, U.S. Geological Survey; WY, water year]

Time period	Tribal Hatchery site (USGS 12310100)					
	Total Suspended		Sands		Fines	
	Acoustic surrogate rating	Streamflow surrogate rating	Acoustic surrogate rating	Streamflow surrogate rating	Acoustic surrogate rating	Streamflow surrogate rating
October	1,800	2,200	300	300	1,500	2,100
November	14,100	14,500	4,300	3,700	9,300	10,600
December	15,600	30,300	4,200	8,800	10,700	20,700
January	3,500	11,300	500	2,600	3,100	8,600
February	4,200	11,500	1,000	3,400	3,100	7,700
March	14,300	21,100	3,600	6,600	10,800	14,200
April	51,000	64,700	14,300	21,500	37,200	43,200
May	81,800	84,500	22,500	25,300	58,100	57,600
June	64,200	58,000	19,300	17,300	43,400	38,900
July	31,000	23,600	10,400	7,100	19,700	15,400
August	10,500	4,400	2,700	900	7,200	3,300
September	4,100	2,200	900	400	3,100	1,900
WY2011	243,900	320,900	59,000	94,700	181,100	220,400
WY2012	384,300	435,500	113,400	129,100	265,700	298,200
WY2013	275,300	267,500	79,000	75,600	192,000	186,800
WY2014	280,900	289,200	84,300	92,200	190,200	191,000
Total water years 2011–14	1,184,400	1,313,100	335,700	391,600	829,000	896,400
Average annual	296,100	328,300	83,900	97,900	207,300	224,100

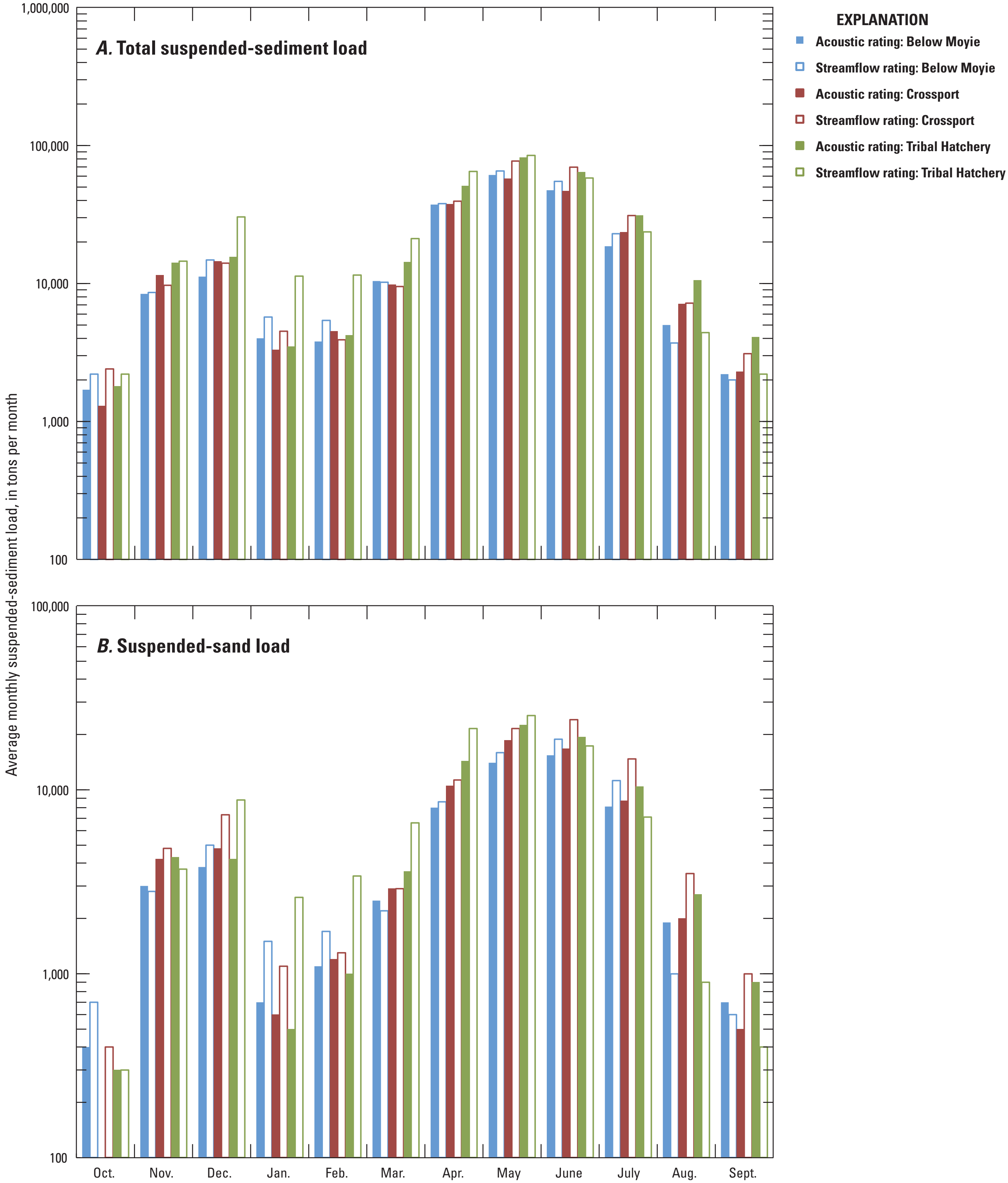


Figure 14. Average (*A*) total suspended-sediment load and (*B*) suspended-sand load by month on the basis of acoustic and streamflow surrogate ratings at Below Moyie, Crossport, and Tribal Hatchery sites, Kootenai River, Idaho, water years 2011–14.

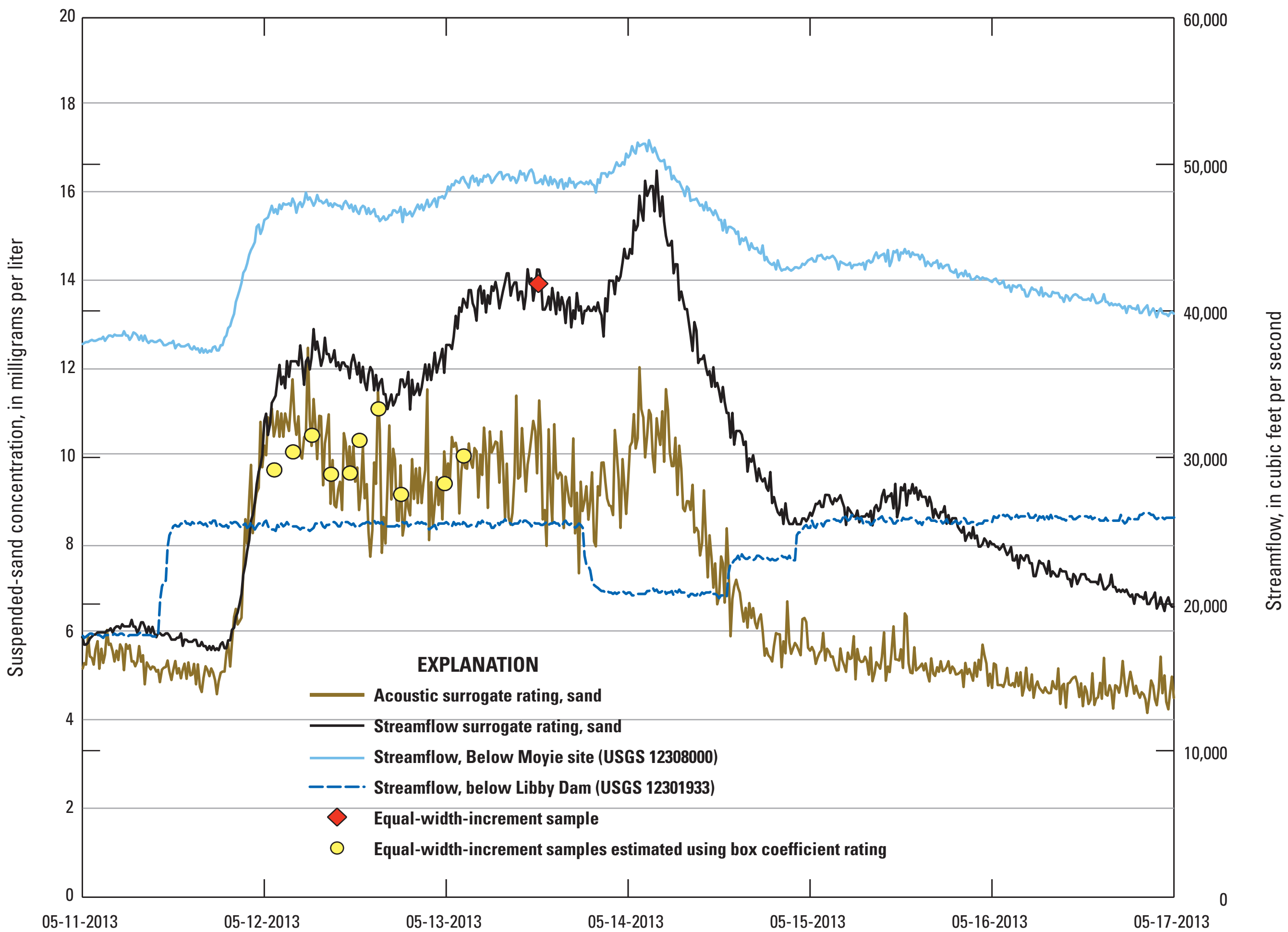


Figure 15. Estimated values of suspended-sand concentration during a storm event, on the basis of surrogate ratings with acoustic backscatter and streamflow, at the Below Moyie site (USGS 12308000), and streamflow at the Below Moyie site and below Libby Dam (12301933), Kootenai River, Idaho, May 11–17, 2013.

The sand concentration in that sample (14 mg/L) was within the 95-percent prediction intervals for the acoustic surrogate rating (7.4–17 mg/L); note that the prediction intervals are not displayed in figure 15 because of the complexity of the graph. The sand concentrations estimated using the streamflow surrogate rating peaked on the highest streamflow peak on May 14, but no samples were collected on this peak to verify either rating for this response. Overall, the streamflow surrogate ratings tended to produce estimates of peak sediment concentration that coincided with the peak in streamflow, which was not typically true for the Kootenai River because sediment contributions from tributaries did not necessarily coincide with timing of peak streamflow. The streamflow surrogate ratings generally produced higher suspended-sediment and sand concentrations and loads on the falling limb of the hydrograph than the acoustic surrogate ratings, particularly for streamflows in late May, June, and July. Most of the limited samples collected on the falling limb of the hydrograph verified the estimates produced by the acoustic surrogate rating. Similar results were observed at all sites.

Total suspended-sediment and sand concentrations estimated by the streamflow and acoustic surrogate ratings also were compared for the four verification samples collected in 2014. This comparison was perhaps the most appropriate comparison of the two ratings because none of the 2014 samples were used to create the ratings. The 2014 samples were collected during elevated releases from Libby Dam as part of the “sturgeon pulse” and elevated streamflows from tributaries between Libby Dam and the study sites.

The sample results closely matched the acoustic surrogate rating estimates, particularly for SSC at the Below Moyie site (fig. 16), although similar results were observed at all sites. Sand concentrations in the samples were low (2–7 mg/L) but generally were closer to the acoustic surrogate rating estimates than the streamflow surrogate rating estimates, except for the last sample collected on June 11, 2014, at the Below Moyie site, which was closer to the streamflow surrogate rating. The differences in SSC and sand concentrations between the two ratings were greatest during periods of elevated releases from Libby Dam (fig. 16). The streamflow surrogate rating appeared to overestimate SSC and sand concentrations during these periods, because of the inclusion of the streamflow-based explanatory variables.

The use of the LDR and seasonality terms improved the estimates made using the streamflow surrogate ratings in comparison with a rating on the basis of streamflow alone, but the streamflow surrogate ratings still produced artificially high peak SSC and SSL estimates associated with peak streamflows. Sample results showed that the coincidence of high SSL and streamflow was not always true, particularly during periods of high releases from Libby Dam, which have low SSL on the basis of visual observations. Overall, the acoustic surrogate ratings appeared to provide a more direct measure of suspended sediment, incorporating variable sediment sources and inconsistent relations with streamflow, than did the streamflow surrogate ratings. Additionally, the acoustic surrogate ratings are expected to be more representative for measuring responses to changes in channel design and streamflow regimes than are the streamflow surrogate ratings, which are representative only if the relation between the magnitude and timing of streamflow and associated SSL does not change.

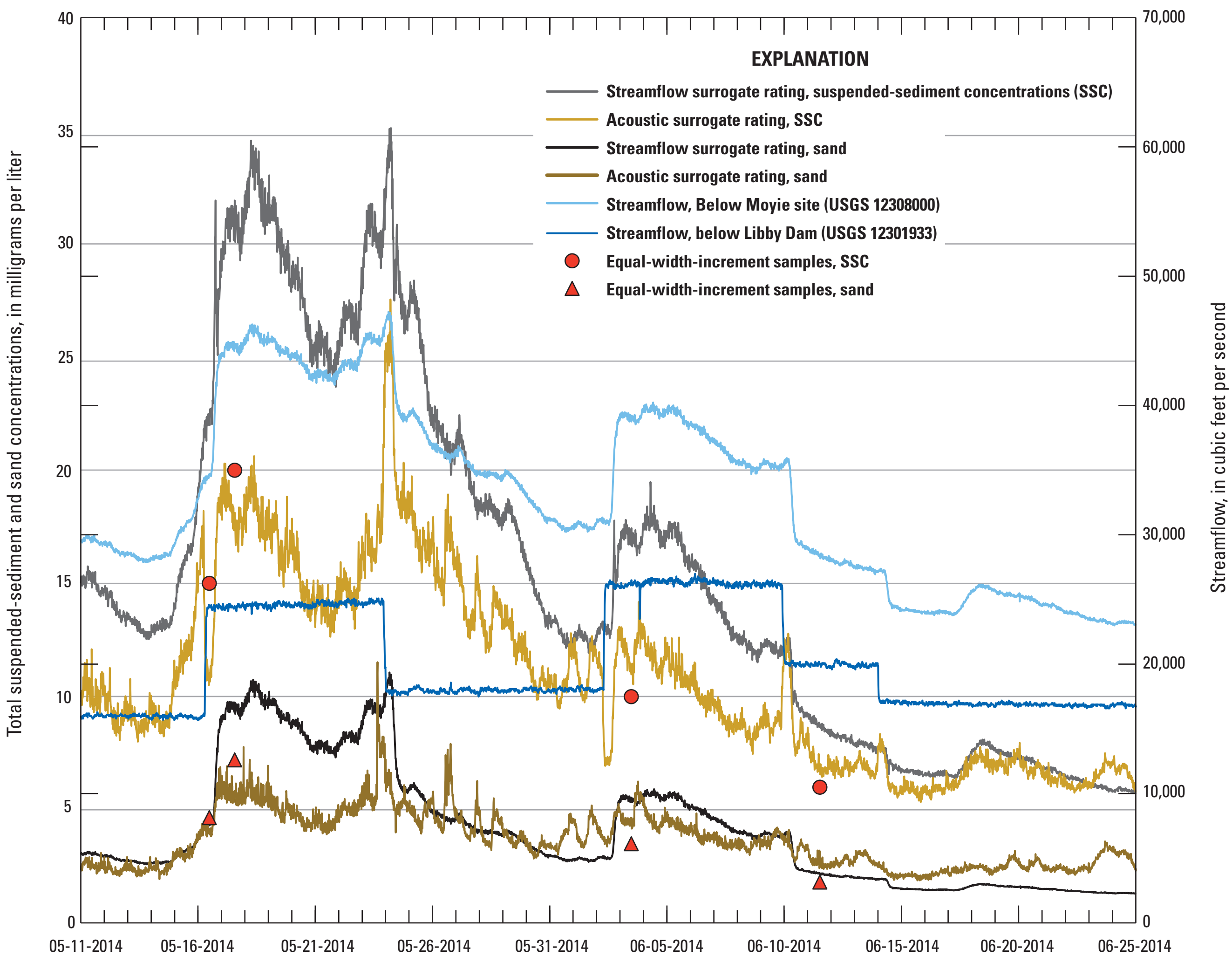


Figure 16. Estimated total suspended-sediment and sand concentrations, on the basis of surrogate ratings with acoustic backscatter and streamflow, at the Below Moyie site (USGS 12308000), and streamflow at the Below Moyie site and below Libby Dam (12301933), Kootenai River, Idaho, May–June 2014.

Potential Areas for Further Study

Use of acoustic backscatter has shown promise for estimating a continuous record of SSC in the Kootenai River. Continued operation of the acoustic surrogate sites and use of the acoustic surrogate ratings to calculate continuous SSC and SSL will allow for tracking long-term sediment transport trends following implementation of the Kootenai River Habitat Restoration Program. The results of the sediment surrogate ratings must be verified and validated over time by collecting additional suspended-sediment samples. A minimum of four, but preferably seven, suspended-sediment samples should be collected per year over a range of hydrologic and sediment conditions and compared to rating results, as long as the ratings are used to generate SSC and SSL estimates. Time periods and conditions that should be targeted when collecting samples in the future include:

- Winter FRM operations (December), when high streamflow releases from Libby Dam have the capacity to mobilize sand deposited on the streambed;
- January or February, to verify which sediment surrogate rating method produces more accurate estimates of SSL during periods of discrepancies in results between the two methods;
- early spring during the rising limb of a rain-on-snow or snowmelt runoff event in tributary basins;
- early spring during the falling limb of a rain-on-snow or snowmelt runoff event in tributary basins;
- rising limb of the spring freshet or sturgeon pulse;
- falling limb of the spring freshet or sturgeon pulse; and
- mid- to late summer during the extended falling limb of the hydrograph or during baseflow conditions.

Ratings may need to be revised or extended over time if sample results show changes in sediment transport conditions or substantially higher sediment transport than what was represented by samples collected during rating development in 2011–13.

The bed material load in the study reach predominantly consists of sand, and the suspended sand relations currently exhibit the highest uncertainty. Considering this, the acoustic surrogate ratings for suspended sand concentration might be improved by installing ADVMs lower in the water column at the study sites. The goal of installing the additional ADVMs would be to target a zone of water that contains a consistently higher sand concentration than currently measured in the ADVM measurement volume and that has a more consistent, proportional relation with sand concentrations measured in the EWI samples.

Currently, the ADVMs measure backscatter at a fixed horizontal location, but in the future, backscatter and sediment variations across the entire stream channel might be measured using an acoustic Doppler current profiler (ADCP). An ADCP can be pulled across the stream from a boat on the water surface, looking down into the water column, and ADCPs are commonly used to measure streamflow at the Kootenai River study sites. Ancillary data collected using the ADCPs during the streamflow measurement could be used to estimate SSC using ratings developed with EWI and grab samples along with the fixed acoustic surrogates. Some early research and software development (described in Boldt [2015]) indicates this is possible, although some research and operational questions remain before the method can be widely used, most notably adapting and correcting acoustic backscatter calculations for changing sediment concentrations, characteristics, and attenuation with water depth.

A supplemental area to consider for future study would be to develop a better understanding of the quantity and timing of sediment contributions from upstream tributaries and streambank erosion. A large historical data set containing suspended-sediment data, and bedload data to a lesser degree, was collected by the USGS and National Forest Service from the late 1960s through about 2014 on numerous Kootenai River tributaries downstream of Libby Dam (Holnbeck and Lawlor, 2008). Developing streamflow surrogate ratings using available data for selected tributaries, and collecting additional data on other tributaries, might help describe sediment transport in the critical habitat by addressing three questions:

1. Are the fines/sands/gravels stored primarily in the river or input from tributaries?
2. Which tributaries contribute the most fines/sands/gravels?
3. How does the estimated tributary contribution compare to the estimated sediment transported in the critical habitat study reach?

Additionally, a growing area of research has been focused on sediment fingerprinting, which could help identify specific sources of sediment in the Kootenai River and, if possible, steer sediment management strategies. Sediment fingerprinting research has been used in the development of sediment total maximum daily loads and associated management (Gellis and Noe, 2013; Gellis and others, 2015). Although the focus of many of these studies has been on managing sediment as a pollutant in impaired waters, the concept of sediment fingerprinting could be used in the Kootenai River to confirm whether certain types of sediment come from streambank erosion or from tributary contributions and whether sources change over time.

Summary and Conclusions

The U.S. Geological Survey, in cooperation with the Kootenai Tribe of Idaho (KTOI), collected suspended-sediment and bedload data and evaluated the use of acoustic backscatter and streamflow as surrogate technologies to estimate suspended-sediment concentrations (SSC) and suspended-sediment loads (SSL) in the Kootenai River during water years 2011–14. The purpose of the work was to document suspended and bed sediment transport conditions for use in KTOI and River Design Group, Inc. efforts to evaluate habitat, model sediment transport, and design and adaptively manage river channel modifications to encourage recruitment and survival of white sturgeon and other native fish species in the Kootenai River. Data were collected at three sites on the Kootenai River in water years 2011–14: downstream of the confluence with the Moyie River, at Crossport, and at the Tribal Hatchery near Bonners Ferry, Idaho. Study sites were selected primarily to measure suspended-sediment transport in the upstream end of the braided reach, within the braided reach, and in the meander reach of the river and to coincide with key locations of the restoration design and sediment modeling efforts. Suspended-sediment samples were collected at all three sites, and bedload samples were collected only at the Crossport site. Acoustic surrogate ratings were developed for total SSC, sand, and fines concentrations using backscatter readings from acoustic Doppler velocity meters (ADVMs) and, for some sites and types of sediment, using a ratio representing streamflow contributions from tributaries. Results from the acoustic surrogate ratings were compared to results from surrogate ratings developed using the USGS R-LOADEST program with streamflow and seasonality explanatory variables.

Mean annual streamflows in water years 2011–14 generally were above average compared to the mean annual streamflow from the 1975–2015 (post Libby Dam) period of record for the Kootenai River at Leonia (USGS 12305000). Additionally, variable discharge or streamflow (VARQ) operations at Libby Dam provided increased spring streamflow and decreased autumn streamflow periods compared to prior years in the Libby Dam era. SSC and fines concentrations were driven primarily by contributions from the tributaries between Libby Dam and the study area and were highest during rain-on-snow events in those tributary watersheds. On average, the relative percentage of SSC in samples collected in water years 2011–14 composed of fines less than 0.0625 mm was 73, 71, and 70 percent at the Below Moyie, Crossport, and Tribal Hatchery sites, respectively. Sand transport was observed to increase with higher flows, typically but not always associated with releases from Libby Dam. Streamflows released from Libby Dam had low sediment concentrations, so the source of sand measured at the study sites during high streamflows was expected to be from (1) upstream tributaries, immediately transported to the study area; (2) upstream tributaries, deposited in the river upstream of the study area and re-suspended and transported during high streamflows; (3) streambank erosion; or (4) a combination of each.

Bedload measured at the Crossport site averaged about 5 percent of the total sediment load measured in samples collected in water years 2011–13 and was positively correlated with SSL. Bedload contained 95 percent gravel and 4 percent sand on average among all samples. Results of the SSL for all three sites and bedload at the Crossport site in relation to drainage area were compared to regression and envelope lines developed from results of samples collected during comparative conditions, in relation to drainage area, in other rivers in the Western United States. The comparisons showed that suspended-sediment and bedload transport in the Kootenai River was substantially lower than estimated by the suspended-sediment transport regression and envelope lines for minimally regulated rivers in the northern Rocky Mountains, primarily because of anthropogenic influences and streamflow regulation, which have limited the variability of streamflow, sediment supply, and natural sediment transport processes.

Acoustic surrogate ratings were successfully fit to the sampled SSCs at all sites. Inclusion of a Libby Dam Ratio term, representing relative streamflow contributions from unregulated tributaries, improved the rating fit for SSC and fines concentrations but not for sand concentrations. At the Below Moyie and Crossport sites where two ADVMs of different frequencies were installed, total and fines concentrations were best fitted with ratings developed using the higher frequency ADVM (3-MHz), which was expected on the basis of past research and acoustic theory. Sand concentrations were best fitted with ratings developed using the lower frequency ADVM (1.5-MHz). Ratings for total suspended-sediment, fines, and sands concentrations were successfully fitted to a single frequency 1.5-MHz ADVM at the Tribal Hatchery site, although estimates would probably have been improved if a second frequency ADVM had been used. The relations between corrected acoustic backscatter and total suspended-sediment, sand, and fines concentrations at the Below Moyie and Crossport sites all showed breakpoints or changes in rating slope, which varied by site and sediment type. As a result, different ratings were prescribed to estimate sediment concentrations whether corrected acoustic backscatter was above or below the rating breakpoint. Rating error at high SSC might have partially resulted from vertical stratification of sediment (particularly sand), which was not always well-represented in the fixed-depth, horizontal sampling volume of the ADVMs. Improved estimates of SSC when sand concentrations are high might be obtained by installing an ADVM lower in the water column to measure backscatter in zones where higher sand concentrations are probably transported. Rating error at low SSC and sand was probably because of relatively low concentrations overall and operational limits of the ADVM backscatter measurements.

The streamflow surrogate ratings produced average annual SSL estimates that were 8–32 percent higher, depending on site and sediment type, than estimates produced using the acoustic surrogate ratings. The greatest differences between the streamflow and acoustic surrogate ratings were observed for sand (streamflow rating estimates 16–32 percent higher) and particularly for the ratings at the Crossport site compared to the other sites (streamflow rating estimates 23–32 percent higher). The streamflow surrogate ratings at the Crossport site produced annual SSL estimates that did not align well with estimates from other streamflow surrogate ratings at the upstream Below Moyie site and downstream Tribal Hatchery site.

Overall, the streamflow surrogate ratings tended to produce estimates of peak sediment concentration that coincided with the peak in streamflow, which was not typically true for the Kootenai River because sediment contributions from tributaries did not necessarily coincide with timing of peak streamflow. The streamflow surrogate ratings generally produced higher suspended-sediment and sand concentrations and loads on the falling limb of the hydrograph than did the acoustic surrogate ratings, particularly for streamflows in late May, June, and July. Most of the limited samples collected on the falling limb of the hydrograph verified the estimates produced by the acoustic surrogate rating. Similar results were observed at all sites. Results of samples collected in water year 2014 were not used in rating development but were retained for validation of rating results. These sample results more closely matched the acoustic surrogate rating estimates than the streamflow surrogate rating estimates.

Acoustic surrogate technologies can be a cost-effective component of a long-term fluvial sediment monitoring program. Once an initial regression model is developed between acoustic surrogate data and SSC, samples can be collected less frequently, perhaps reducing long-term operation and maintenance costs for a sediment monitoring station. Sediment surrogates also allow the estimation of sediment when it is unsafe to sample the stream, such as during extreme flood events, though care should be taken not to apply sediment surrogate ratings far beyond the range of variables used to develop the ratings. Inspection of the sediment record, estimated using a surrogate rating, might reveal significant episodic sediment-transport events that would be difficult to detect otherwise. Suspended-sediment estimation techniques using streamflow alone might provide poor results over small time scales or in streams with partially regulated streamflow, episodic sediment sources, and non-equilibrium sediment transport, as is the case for the Kootenai River. Acoustic surrogate technologies are an effective and more direct means to obtain continuous, accurate estimates of SSC and SSL for general monitoring and sediment-transport modeling than use of streamflow. In the Kootenai River, continued operation of the acoustic surrogate sites and use of the acoustic surrogate ratings to calculate continuous SSC and SSL will allow for measuring long-term trends in sediment transport and supply following implementation of the Kootenai River Habitat Restoration Program.

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Appendix A. Analytical and Related Data for Sediment Samples Collected at Sediment Monitoring Sites in the Kootenai River, Idaho, Water Years 2011–14

Appendix A tables (Excel® file) are available for download at. http://dx.doi.org/10.3133/sir20155169.

Table A1. Results of equal-width-increment suspended sediment samples collected and estimated using box coefficient ratings in the Kootenai River below Moyie River near Bonners Ferry, Idaho (USGS 12308000), water years 2011–14.

Table A2. Results of unattended suspended sediment samples collected using an autosampler in the Kootenai River below Moyie River near Bonners Ferry, Idaho (USGS 12308000), water years 2012–13.

Table A3. Results of equal-width-increment suspended sediment samples collected and estimated using box coefficient ratings in the Kootenai River at Crossport near Bonners Ferry, Idaho (USGS 12308500), water years 2011–14.

Table A4. Results of unattended suspended sediment samples collected using an autosampler in the Kootenai River at Crossport near Bonners Ferry, Idaho (USGS 12308500), water years 2012–13.

Table A5. Results of bedload sediment samples collected in the Kootenai River at Crossport near Bonners Ferry, Idaho (USGS 12308500), water years 2011–13.

Table A6. Results of equal-width-increment suspended sediment samples collected in the Kootenai River at Tribal Hatchery near Bonners Ferry, Idaho (USGS 12310100), water years 2011–14.

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